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Road traffic noise simulations based on 3D city models

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Abstract

Urban development and densification cause noise problems that can have a negative impact on human health. In 2002, the European Union (EU) stated the European Noise Directive (END) with the purpose to evaluate environmental noise levels (including the sources road, railway, and air traffic) in the member states every 5 years. To make the result of the evaluations comparable between countries, the CNOSSOS-EU model has been provided as a noise simulation standard.

Noise simulations require information about noise sources and propagation conditions. For this geographic information is required such as 3D city models and road databases. In Sweden there is an ongoing work to standardize 3D city models denoted as the 3CIM model. This thesis aims to evaluate the capability of 3CIM to be used as input data in road traffic noise simulations in accordance to the END-directive. To make the original data readable in the SoundPLAN noise simulation software, the 3CIM and road datasets, together with a height model (DEM) was tailored in FME to generate the input data. By mapping attributes, the input data was imported to SoundPLAN. The noise simulation output consisted of a map presenting noise levels on the façade were as well as noise level tables for noise sources and receivers.

The thesis discusses the limitation of the current 3CIM and road datasets as input data for noise simulations as well as the problems that may occur when performing noise simulations in SoundPLAN. Finally, it provides possible solutions to improve the input data, and solve the programming running problems.

Keywords: 3D city model, 3CIM, CNOSSOS-EU, noise simulation, city noise evaluation, data tailor, FME, SoundPLAN

Abbreviations

3CIM: 3D City Information Model

3D: three-dimension/three-dimensional

3DCM: 3D City Model

ADE: Application Domain Extension

API: Application Programming Interface

ASCII: American Standard Code for Information Interchange

BIM: Building Information Model

CAD: Computer-Aided Design

CityGML: City Geography Markup Language

CityJSON: City JavaScript Object Notation

CNOSSOS-EU: Common Noise Assessment Methods in Europe

CRTN/CoRTN: Calculation of Road Traffic Noise

DGM: Digital Ground Model

DTM: Digital Terrain Model

END: Environmental Noise Directive

ETL: Extract Transform Load

FME: Feature Manipulation Engine

FNM: Façade Noise Map

GDI: Geodateninfrastruktur (Spatial Data Infrastructure Germany)

GML: Geography Markup Language

ISO: International Organization of Standardization

JSON: JavaScript Object Notation

LVDB: Lokala Vägdatabasen

NMPB: Nouvelle Méthode du Prévision de Bruit

NMT: Nordic prediction Method for Train noise

NRW: North Rhine-Westphalia

NVDB: National Road Database (Sweden)

OGC: Open Geospatial Consortium

OpenGL: Open Graphics Library

RMW: Reken en meetvoorschrift Verkeerslawaai

RTN: Road Traffic Noise

SGI: Statens Geotekniska Institut

SGU: Sveriges Geotekniska Undersökning

SIG: Special Interest Group

SPS: Single Points receiver Sound

TIN: Triangular Irregular Networks

WHO: World Health Organization

XML: Extensible Markup Language

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1 Introduction

1.1 Background

With the ongoing urbanization and densification of urban areas, traffic noise has become an omnipresent harmful form of environmental pollution globally (Den Boer & Schroten, 2007). According to the WHO report in 2007, over 40% of Europeans were exposed to road traffic noise that was higher than 55dB, a level potentially dangerous to health (Den Boer & Schroten, 2007), and at that point a health-based guideline value from WHO (Berglund et al., 1999). Being regularly exposed to high noise levels can cause health problems such as annoyance, sleep disturbances, cardiovascular disease, deafness, depression, and insomnia (Kavisha et al., 2017; World Health Organization, 2019). Measuring the noise level in an urban environment is difficult, especially if you want to be able to differentiate noise from different sources (de Kluijver & Stoter, 2003). It is possible to measure noise, but difficult and resource-demanding. A limitation with measuring is also that you can only record the present noise level and the collected data cannot represent a past or future situation (de Kluijver & Stoter, 2003). Hence, a more resource-efficient way that enables assessments of source-specific noise as well as studying different scenarios is to perform simulations to evaluate urban noise levels. These types of simulations can act as a decision basis and help city planners and decision-makers to improve the sound environment in urban areas and thereby improve living conditions.

Several noise simulation softwares have been developed based on the noise mapping frameworks in various countries and areas. Examples are GeoMilieu based on the Dutch noise calculation methods (DGMR, 2014; Kavisha et al., 2017), CadnaA based on DIN45678, and ISO 17534 standards (Datakustik GmbH, 2014). One noise simulation software that it implements a number of noise mapping frameworks, for example, CNOSSOS-EU: 2021/2015 (Common Noise Assessment Methods in Europe) (Kephalopoulos et al. 2012) is SoundPLANoise 8.2. It has been implemented and tested according to ISO 17354-4[1] and the national specifications of various countries, for instance, in Malaysia (Abdullah et al., 2009) and Greece (Hadzi-Nikolova et al., 2012).

In order to survey noise exposure in Europe the EU (European Union) has launched the END (Environmental Noise Directive) (Directive, 2002) and CNOSSOS-EU (Kephalopoulos et al. 2012) as a common model to harmonize the reporting on EU-level. Previously the EU Member states developed their local, regional, and national noise assessment models. Examples are RMW in the Netherlands, NMPB in France, and CRTN in the UK (Kumar et al., 2020). In Sweden, the Nordic Road Traffic Noise prediction model last revised in 1996 is still being used for national purposes (RTN96) (Naturvårdsverket et al. 1996). From 1996 to 2000, a new model Nordic2000 was developed by the Nordic nations and used by Finland (Kokkonen et al., 2016), although the old model is still the most used.

The results from different noise simulations can vary significantly depending on which model is implemented (for instance CNOSSOS), the quality of the input data, software used and the parameter setting made by the user (Jonasson & Gustafson, 2010; de Kluijver & Stoter, 2003). According to the needs, different LoDs (Level of Details) of input data can be imported into the models to calculate the noise levels (Czerwinski et al., 2007; Kavisha et al., 2017). Compared to 2D data, introducing 3D city model

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[1] ISO 17354-4: https://www.iso.org/obp/ui/#iso:std:iso:tr:17534:-4:ed-1:v1:en

(3DCM) in noise simulation could improve the results by taking more factors into consideration. One of the reasons is that a 3DCM can enclose building façades, as well as windows, balconies, etc. affecting the noise level (Ford & Kerry, 1973). In order to evaluate the use of the Swedish national 3DCM in the noise simulation field, this project introduced a 3DCM as a solution to input data into the noise simulation software. A 3DCM represents the urban environment with three-dimension geometric and semantic urban objects and structures (Biljecki et al., 2015). It has been applied to urban planning (Sinning-Meister et al., 1996), urban energy system modeling (Krüger & Kolbe, 2012), real-time visualization (Beck, 2003), etc. Each application requires specific 3D data and a comprehensive 3DCM that can be used for all purposes does not exist (Biljecki et al., 2015). Based on the needs, a 3DCM can be stored in various standards. The most common open standard is CityGML which is based on a GML/XML schema with an Application Domain Extension (ADE) in a specific field such as noise simulation (Gröger & Plümer, 2012). The CityGML schema encloses both geometry and semantic city object that enables data exchange, advanced analysis, and visualization tasks (Gröger & Plümer, 2012). With an ADE, CityGML can be applied in specific cases for data modeling, simulation, and evaluation (Biljecki et al., 2018). Another commonly used standard for 3DCM is CityJSON which is based on the JSON format with the aims to take advantage of its compactness in web development (CityJSON files from real-world datasets are on average 6× more compact). In addition, the CityJSON structure can be parsed and manipulated easily by many programming languages, including JavaScript (Ledoux et al. 2019).

The input data for noise simulation models extracted from various registers and databases as well as the assessment methods are different (Kumar et al., 2020). The project 3CIM (3D City Information Model) defines a profile of Swedish national 3D city models based on CityGML (3CIM Project[2]). The aim of the 3CIM project is that the 3CIM specifications should support many applications in the built environment process such as noise simulations and sunlight simulations. As a part of the 3CIM project, in this study, we evaluate the use of 3CIM, together with the height model and local road databases, in road traffic noise simulations.

1.2 Problem statement

In 2020, the three main cities in Sweden Stockholm Gothenburg and Malmö, together with Lund University, started a standardization of 3D city models denoted 3CIM, which is a national profile based on CityGML. As a very openly formulated standard, it is hard to develop a general import interface for CityGML to a specific application (Ledoux et al., 2019). Also, the 3CIM data is not able to be imported directly by the noise simulation software. Therefore, finding a workflow to transform 3CIM and prepare input data for noise simulation software is necessary to facilitate noise studies as well as other 3CIM application studies. Additionally, there need to be a connection to road datasets which commonly contains information that are not included in 3CIM, such as road surface properties and traffic intensity.

1.3 Aims

The general aim of the master thesis is to evaluate the capability of 3D city models to be used as input data to noise simulations. The following research questions are addressed:

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[2] 3CIM Project: https://www.smartbuilt.se/in-english/projects/open-call-8/3cim/

1) What are the requirements of the noise simulation software in this study? Identify a noise simulation software that satisfies these requirements that should be used in this study.
2) In addition to the 3D city model 3CIM, what other data (e.g. geographic and road data) are required in the noise simulation process?
3) How to tailor the required data to act as input data for noise simulation? For the geometries, how to make the data with specific data format and specific geometries readable in the selected noise simulation software? For the semantics, how to generate the required parameters for evaluating noise levels?
4) What are the shortages of the 3CIM specifications and other input data? For the geometries, are there any objects that affect the noise simulation accuracy? For the semantics, are there any missing attributes that affects the simulation result? Further, what are the possible solutions to improve the input data.

1.4 Limitations

The study has the following limitations:

1) The study only examines the CNOSSOS-EU noise simulation model. The required parameters and calculation methods vary from model to model. Thus, the solution may not fit for other noise models.

2) The study selected only one noise simulation software SoundPLAN. For other noise tools, the data preparation could be different.

3) The study focused on a study area in Malmö, Skåne, south Sweden. The terrain, building types, road types, etc. are likely different in other study areas. For instance, buildings with complex structure such as covered bridges or domes and steep roads in a mountainous city. These should be taken into consideration in further studies.

4) The main source of noise in this study area is road traffic, while no railway traffic, airplane as well as industrial noise is enclosed. These noise sources have their own simulation models and to some part different input data and could be evaluated in other studies.

1.5 Disposition

After the introduction, the thesis is split into five chapters: Chapter two introduces the theory of related works, which covers the development of noise simulation models, the introduction of SoundPLAN software, basic knowledge about 3D city models as well as other data sources. Chapter three describes the case study in Malmö Stad. It starts by introducing the study area, then describes the data sources, including the 3CIM data, road dataset and the height model. After that, it clarifies the reason to select SoundPLAN as the noise simulation software, and the methods for tailoring the original data to fit the software. Finally, it displays the input data to noise simulation software, as well as the noise simulation results. Chapter four discusses the limitation of original data and provides possible solutions to improve the data. In addition, it points out the possible problems that may occur when performing noise simulations then gives solutions to continue the program. Chapter five concludes the thesis project by answering the research questions.

2 Theory of Related Works

This chapter introduces the theory of related works. Section 2.1 describes the development of the noise simulation model CNOSSOS-EU and its implementation in the Nordic countries, especially in Sweden. In Section 2.2 the theoretical framework and mathematical formulae's that CNOSSOS-EU uses to calculate road traffic noise are described. Section 2.3 introduces the noise simulation software used in this study, including the supported noise simulation models, the required input data type, the required input data formats, and the noise simulation results generated from the software. Section 2.4 introduces the concept of 3D city models and the commonly used methods to generate a 3DCM. It describes the 3DCM development in big cities and their applications, then introduces the standardization of 3DCM data formats. Section 2.5 presents the CityGML concept and the latest version that has been developed. 2.5.1 detailly described the themes in CityGML 2.0. In 2.5.2 and 2.5.3, the concepts of the Level of Details (LoDs) and the Application Domain Extension (ADE) are being introduced respectively. Section 2.6 is dedicated to explaining the 3CIM model. This section introduces the relationship and differences between 3CIM and CityGML. Furthermore, described the themes in 3CIM and the connected external databases. Section 2.7 summarizes how 3DCMs were utilized in noise prediction models and the noise ADE developed in different countries. Section 2.8 introduced the road dataset which was from the Local Road Database (LVDB).

2.1 Noise Simulation Models

In order to assess exposure to environmental noise and adopt action plans to improve the urban living environment, the European Parliament and the Council launched the END (European Noise Directive) since 2002. It requires the member states to produce strategic noise maps and communicate the information/limit values to the Commission every five years. In this directive, the recommended noise assessment approaches are mainly for the counties that had no national computation methods or intended to change the methods (Directive, 2002).

During the first round of strategic noise mapping (2002-2007), there was no harmonized method legally binding to the member states and some of them had their own national computation methods (Kephalopoulos et al., 2012), for instance, RMW in the Netherlands, NMPB in France, CRTN in the UK (Kumar et al., 2020), and the Nordic Road Traffic Noise Prediction Model in Sweden (Naturvårdsverket et al. 1996). The national assessment methods differed from the interim methods for 13 of the member states, which made it hard to present consistent and comparable noise assessment results across the member states. To help the member states fulfill their obligations under the END, the Commission started to develop the common method CNOSSOS-EU in 2008 to assess the noise level in Europe (END Report 2011[3]; Kephalopoulos et al., 2012).

Until the end of the third round of the END strategic noise mapping (2017), the CNOSSOS-EU was only used by Finland, while 30 different assessment methods were used in other countries (Kumar et al., 2020). However, the new version CNOSSOS-EU published in 2015 shall replace the national noise assessment methods before the end of 2018. In the next round of strategic noise mapping (2021/2022), the harmonized method must be applied across the EU (Vergoed & van Leeuwen, 2018). Moreover, some noise simulation methods were updated based on CNOSSOS-EU, examples are

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[3] END report 2021: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52011DC0321

road traffic noise models sonROAD18 in Switzerland (Heutschi et al., 2018) and Nord2000 in Finland (Kokkonen et al., 2016).

For the Nordic countries, including Sweden, the Nordic prediction method RTN96 is still used as the primary road noise calculation method. It has officially been used for about 20 years and the method is very different compared to CNOSSOS-EU (Kokkonen et al., 2016). From 1996 to 2000, the Nordic countries developed a new Nordic method Nord2000 for predicting road traffic noise (Jonasson & Storeheier, 2001). The input values for the new method Nordic2000 are more detailed and recently measured compared with that for RTN96. The values for Nordic2000 are much easier to be transferred to CNOSSOS-EU (Kokkonen et al., 2016). However, to fulfill the END requirements, the Nordic countries skipped Nordic2000 and attended to apply CNOSSOS-EU directly.

2.2 CNOSSOS-EU

CNOSSOS-EU (Common NOise aSSessment methOds in the European Union) is a common noise assessment method across the EU member states. It was developed for harmonizing the data collecting methods, data quality, data availability, data reporting, and assessment methods used in EU member states. CNOSSOS-EU is described in Kephalopoulos et al. (2012), from which the formulas 3-11 in the description of CNOSSOS-EU below are taken.

Generally, the noise level L_p (dB) can be calculated from two parts: sound pressure L_w (dB) which describes the source of the noise, and the effect caused by sound propagation $\Sigma\Delta_{propagation\ factors}$ (Van Leeuwen, 2000) (Formula 1). The calculation for sound pressure L_w and sound propagation $\Sigma\Delta_{propagation\ factors}$ will be interpreted in Section 2.2.1 and Section 2.2.2 respectively.

For the sound pressure L_w, CNOSSOS provides the methods to estimate road traffic noise, railway traffic noise, industrial noise, and aircraft noise emission. The details of Road traffic noise emissions are described in 2.2.1. For the sound propagation $\Sigma\Delta_{propagation\ factors}$, CNOSSOS gives sound propagation models in different conditions. The propagation models for land traffic infrastructures are further described in 2.2.2. Section 2.2.3 clarified the method for assigning noise levels to the noise receivers. While section 2.2.4 introduced the noise indicator specified by the European Directive, which is also the indicator used in this study (Kephalopoulos et al. 2012).

$$L_p = L_w + \Sigma\Delta_{propagation\ factors} \tag{1}$$

2.2.1 Road Traffic Noise Emission

The basic statistical model of road traffic noise is a logarithmic function of traffic volume in vehicles per hour Q and the direct distance from the observation point and center of the traffic lane in meters d. In the first model of acoustic noise developed by Bolt et al. (1952), the 50 percentile of traffic noise L_{50} (dB) is calculated according to equation 2:

$$L_{50} = 68 + 8.5\log(Q) - 20\log(d) \tag{2}$$

A series of constants and parameters were then included to improve the accuracy (Quartieri et al., 2009). CNOSSOS uses the logarithmic function and takes the vehicle types m, the speed v of vehicles as well as the frequency f in each interval of the whole acoustic band (octave band) into consideration. In CNOSSOS, the noise pressure generated by a source (e.g. a single vehicle) is split into the rolling noise L_{WR} (dB) that is produced by tire/road interaction and propulsion noise L_{WP} (dB) that is produced by the driveline (e.g. engine, exhaust) of the vehicles. The two types of noise are calculated separately, and both of them contribute to the noise pressure. L_{WR} and L_{WP} are calculated from vehicle types *m* and the reference speed of the vehicle category (see Section III 2.3 and 2.4 of Kephalopoulos et al., 2012). The noise of a single vehicle L_w is:

$$L_w = 10*\lg(10^{L_{WR}/10} + 10^{L_{WP}/10}) \tag{3}$$

A series of single vehicles in each lane form a traffic flow. The noise generated from a traffic flow $L_{W',\,line}$ (dB) considers the noise pressure of a single vehicle L_w in a vehicle type, as well as the average speed of this type of vehicle v_m on this lane and the traffic volume of this vehicle type per hour Q_m

$$L_{W',\,line} = L_w + 10*\lg\,(Q_m/1000v_m) \tag{4}$$

It should be noticed that:

1) The formulas are slightly different according to vehicle types.
2) The model calculates noise level in a default condition. If the conditions, for example, temperature, and road slope are different, the corrective coefficients should be used (Kephalopoulos et al. 2012).

2.2.2 Sound Propagation Models for Land Transport Infrastructures

The noise level of a receiver point L_p (dB) in CNOSSOS can be described as the sound emission from the source L_w subtracted by the attenuation of noise during its propagation from the source to the receiver *A*. Here CNOSSOS uses an *A* to represent the combined factor of sound propagation, it is the same as the $\Sigma\Delta_{propagation\ factors}$ in formula 1:

$$L_p = L_w - A \tag{5}$$

The sound propagation model gives the approach to calculating the attenuation of noise during its outdoor propagation *A* (dB). In the CNOSSOS model, the attenuation is split into three aspects: $A = A_{div} + A_{atm} + A_{boundary}$

1) Sound attenuation caused by geometrical divergence A_{div} (dB), which corresponds to a reduction in the sound level due to the propagation distance. Under the ideal condition without reflecting surface, interference or other background sound, the sound level is reduced with increasing distance from the source (Barry, 1999).
$$A_{div} = 20 * \lg(d) + 11 \tag{6}$$
where *d* is the direct distance between the source and the receiver in meters.
2) Sound attenuation caused by atmospheric absorption A_{atm} (dB):
$$A_{atm} = \alpha_{atm} * d \,/\, 1000 \tag{7}$$
where α_{atm} is the atmospheric attenuation coefficient in dB/km at the nominal center frequency for each frequency band, in accordance with ISO 9613-1.
3) Sound attenuation caused by the boundary of the propagation medium $A_{boundary}$ (dB). It contains two terms: A_{ground} (dB) which is the attenuation due to ground, and A_{dif} (dB) which is the attenuation due to diffraction. *Diffraction* is when the sound wave encounters an obstacle or opening, interference or bending will occur around the corners of an obstacle or through an aperture into the region of the geometrical shadow of the obstacle/aperture (see Appendix I for sound diffraction).

For a given path and frequency band, CNOSSOS gives two scenarios:
a. When there is no diffraction ($A_{dif} = 0$), then $A_{boundary} = A_{ground}$;
b. When there is no ground effect ($A_{ground} = 0$), then $A_{boundary} = A_{dif}$.

In addition, CNOSSOS divides the propagation path into two categories:

1) downward-refraction propagation conditions/favorable conditions F: The effective speed of sound waves increases with altitude in the direction of propagation. The sound rays are curved towards the ground under favorable conditions.
2) homogeneous atmospheric conditions H: The effective speed of sound waves can be considered as constant in all directions and at any point of the propagation space. The sound rays are straight segments under homogeneous conditions.

For the sound attenuation caused by geometrical divergence A_{div} and atmospheric absorption A_{atm}, it can be calculated in the same way in both propagation conditions.

For sound attenuation caused by the boundary of the propagation medium $A_{boundary}$, it is different in accordance with the propagation conditions. The conditions are represented as $A_{boundary,\ F}$ in favorable conditions, and $A_{boundary,\ H}$ in homogenous conditions respectively. The calculating methods of the two-component of $A_{boundary,\ F}$ / $A_{boundary,\ H}$:

1) $A_{ground,\ F}$ / $A_{ground,\ H}$ is based on the acoustic absorption of ground G and the distance between source and receiver. The formulas are described in Chapter VI (4.3) of the CNOSSOS document.
2) $A_{dif,\ F}$ / $A_{dif,\ H}$ depends on the path difference between the diffracted path and the direct path. If there is more than one diffraction, the attenuation also depends on the total distance between the diffraction closest to the source and the diffraction closest to the receiver. The A_{dif} takes ground effect into consideration, therefore, $A_{ground} = 0$ and $A_{boundary} = A_{dif}$. The formulas are described in Chapter VI (4.4) of the CNOSSOS document.

2.2.3 Combined Noise Levels of a Receiver Point

A summary of the CNOSSOS noise level calculation approach is as follows (Kephalopoulos et al. 2012):

1) Each of the sources and receivers of noise is represented by a point with location and height information. For each noise source, the noise pressure L_w is calculated by the noise emission models.
2) Based on the location and height of a source and a receiver, a mean plane that is vertical to the ground surface is generated by the least square linear regression model. The mean plane represents the sound propagation path in a specific direction.
3) For each path (plane), a set of points will be inserted every 1 meter. These points will be used to detect the topography and calculate the parameters A_{div}, A_{atm}, and $A_{boundary}$.
4) For each path (plane) in the short-distant noise propagation, the sound attenuation, as well as the noise level in either favorable L_F or homogeneous L_H conditions, will be calculated. For noise calculation in long distances, both atmospheric conditions will be taken into consideration. By giving a mean

occurrence of favorable condition p, the noise level of a receiver in one direction L_{LT} can be represented as:

$$L_{LT} = 10 * \lg(p*10^{L_F/10} + (1-p)*10^{L_H/10}) \qquad (8)$$

where L_F is the receiver noise level in favorable conditions and L_H is the receiver noise level in homogenous conditions. A propagation path may contain both conditions. Hence, L_{LT} is the actual receiver noise level from one source in the combined condition.

5) A receiver has more than one source/propagation path, the final noise level $L_{tot,\ LT}$ of one receiver is the combination of noise levels from N sources/propagation paths (see Figure 2.1):

$$L_{tot,\ LT} = 10 * \lg(\Sigma 10^{L_{N,\ LT}/10}) \qquad (9)$$

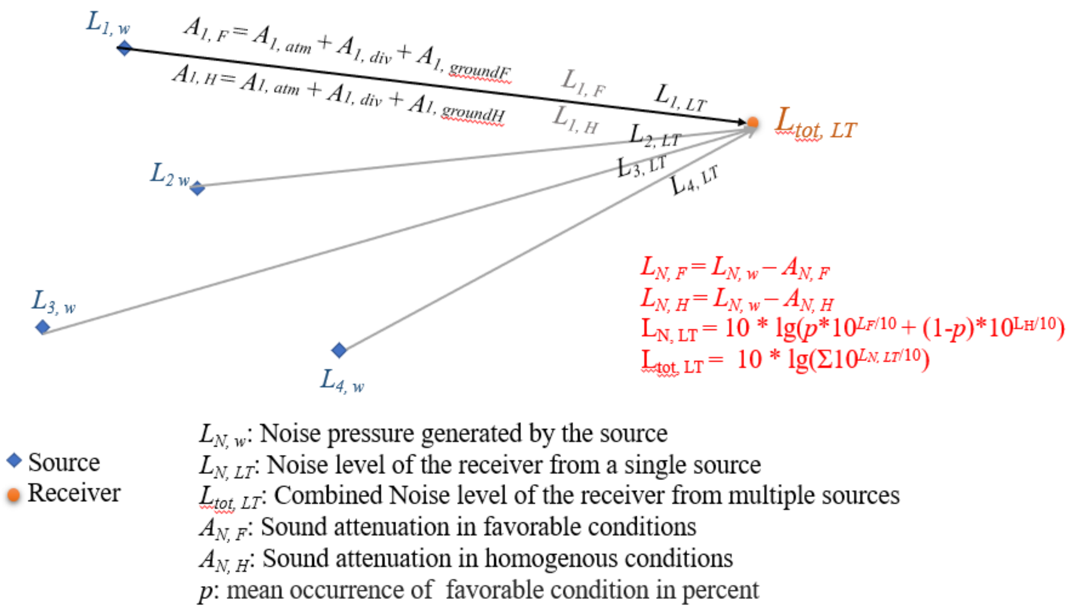

Figure 2.1. Noise level calculation method in CNOSSOS-EU

2.2.4 Noise Indicators

The long-term average noise indicator specified in the European Directive is the day-evening-night indicator, L_{den}. For calculating L_{den}, another noise indicator $L_{eq,T}$ is required. $L_{eq,T}$ is the A-weighted sound pressure level computed by summation over all frequencies:

$$L_{eq,T} = 10 \times \lg\sum 10^{(L_{eq,T,i} + A_{,i})/10} \qquad (10)$$

Where i is the index of the frequency band, A is the A-weighting correction according to the international standard IEC 61672-1.

Noise levels for different time slices (L_{day}, $L_{evening}$, L_{night}) are A-weighting $L_{eq,T}$, as defined in ISO 1996-2:2007. L_{den} is calculated as:

$$L_{den} = 10 * \lg[12/24*10^{Lday/10} + 4/24*10^{(Levening+5)/10} + 8/24*10^{(Lnight+10)/10}] \qquad (11)$$

Meaning that a penalty of 5 dB is added to the equivalent level during the evening and a penalty of 10 dB during the night.

2.2.5 Comparisons between CNOSSOS and Other Models

Researchers have compared CNOSSOS with other noise prediction models. The comparisons were mainly about road traffic noise (Khan et al., 2021; Bertellino et al., 2016; Kokkonen, 2018; Vergoed & van Leeuwen, 2018; Larsson, 2016) and a few about sound propagation (Khan et al., 2021).

CNOSSOS calculates road traffic noise based on the frequency f in octave bands ranging from 63Hz to 8kHz (Kephalopoulos et al. 2012). The model Nord2000 uses the same formulas to calculate noise. However, octave bands in Nord2000 range from 25Hz to 10kHz. In addition, the way the models measure source height, and the vehicle category are slightly different from each other (Khan et al., 2021). Other models, for instance the CoRTN (Calculation of Road Traffic Noise) model in the UK, estimate noise by hourly A-weighted equivalent sound pressure level, which is a different algorithm from CNOSSOS (Kumar et al., 2011).

As for the method to estimate sound propagation, CNOSSOS is based on the French noise prediction model NMPB-2008 (Dutilleux et al., 2008). It uses the principle of ray theory to calculate the attenuation of the sound during its propagation (Khan et al., 2021). The Nord2000 sound propagation model is based on the geometrical ray theory (Kragh, 2011). In addition, the ways the models measure meteorological conditions, receiver height, range of band frequency, geometrical divergence, and diffraction effect are different (Khan et al., 2021).

2.3 SoundPLANnoise

SoundPLANnoise[4] is a software developed by SoundPLAN GmbH in Germany. It offers tools and libraries for noise simulation and noise mapping. The software can estimate noise generated by road traffic, railway traffic, industry, aircraft, and indoor activities and then generate the simulation result in various levels of detail. It has been widely used for assessing and monitoring the urban noise effects (Hadzi-Nikolova et al., 2012; Bozkurt & Demirkale, 2017; Chan et al., 2019).

Many commonly used noise models are supported by SoundPLANnoise, including RTN:1996, Nord2000, and CNOSSOS-EU. The new standards or the latest version standards will be implemented in the current version. Until now, the latest version is SoundPLANnoise 8.2.

For noise simulations, elevation data, as well as city objects such as buildings, roads, and city furniture, are required as input data. Elevation data in the formats ASCII(*.txt, *.csv), ESRI ASCII Grid (*.grd, *.asc), ESRI binary grid (*.adf), GeoTiff (*.tif, *.tiff), LAS (*.las, *.laz), or Winput SCOP can be filtered and then imported to SoundPLANnoise. City objects can be imported as Shapefile(*.shp), Mapinfo Interchange Format (*.mif), ASCII data (*.txt, *.csv), CAD data (*.dxf, *.dwf), 3D Game Model Format (*.gmf), Geography Markup Language (*.gml) format, eXtensive Markup Language (*.xml), etc. (SoundPLAN GmbH, 2019).

Among the city objects, noise sources such as roads, railways, or airports are compulsory input files. The receivers can be generated by various methods, one of which is façade noise map[5]. The façade noise map generates receivers with a constant

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[4] SoundPLANnoise: https://www.soundplan.eu/en/

[5] Façade noise map: https://soundplan.asia/sound-plan-noise/tools/facade-noise-map/

space for each floor of all enabled buildings, while the receivers are outside of the building façade with a specific distance. When making façade noise maps, the receivers such as buildings are also compulsory, since the receivers need to be generated from the input building objects. In addition, users can choose to import the objects as noise barriers and noise absorption ground. Various data sources and data formats can be imported into one project. For instance, a GML file storing a city model and a shapefile storing road data can be used as input data in one simulation process. A detailed explanation of elevation data and objects is as follows:

1) *Elevation model:* A consistent 3D elevation model (ground model referring to the bare earth), which is provided mostly as equidistant grids or as point clouds. After importing the available elevation data (e.g. ASCII format), it will be saved in Geo-Files (*.geo), then a triangulated Digital Ground Model (DGM) can be generated by SoundPLANnoise. The elevation model is the base for data processing and noise simulation.
2) *Objects:* the objects can be created and edited in SoundPLANnoise directly or be imported from existing files. When importing the object as ESRI Shapefiles, each file is a small database that contains a specific object type. Only the building object type can be imported as CityGML, but users can choose to import the buildings as ESRI Shapefiles. SoundPLAN has a special standard dependent on object properties (see Section 4 of SoundPLAN GmbH, 2019). The imported objects contain many properties which may not have an equivalent in SoundPLAN. For instance, SoundPLAN uses “Graphic object ID” to represent the unique ID of a road. If the road ID in the input file is stored as other attribute names (e.g. “GID”), then it should be referenced to the SoundPLAN equivalent when importing the file (SoundPLAN GmbH, 2019).

After importing the input data, SoundPLAN generates a Geo file for each imported file. Then users need to set a series of parameters (e.g. reflection order, max search radius, max reflection distance, allowed tolerance), and select the calculation method/standard for each type of noise emission and noise attenuation. The parameter setting depends on the specific use cases. After running the program, SoundPLAN will give the noise simulation result. Generally, the noise simulation result can be documented as two types:

1) *Tables:* The results of single points receiver calculation are usually documented in tables. For instance, the results of single point receivers sound (SPS), façade noise map (FNM) calculations, and meshed noise maps. The tables include a receiver table, a road emission table, level charts and pass-by level for railways, result table for mean propagation and contribution noise levels, etc.
2) *Graphics:* The results of the grid noise map are usually documented in graphics with values and contour lines and can be exported in various formats. For instance, the result of cross-sectional noise map and grid noise map calculation. The results are only documented in graphic form, not in the format of single receivers.

SoundPLANnoise is able to display the results in 3D using the graphics 3D-standard OpenGL 4.1. A noise map is generated for the selected viewpoint with a self-defined resolution. The scene can be stored as *.bmp, *.jpg, *.png, and *.tif files (SoundPLAN GmbH, 2019).

2.4 3D City Models

A 3D City Model (3DCM) is a digital model of a city (Chen, 2011), which represents the urban environment with a three-dimension geometry of urban objects and structure (Biljecki et al., 2015). Generally, it can be generated by terrestrial measurement techniques, high-resolution satellite/aerial images/laser scanning, or terrestrial images/laser scanning (Singh et al., 2013). A 3DCM contains a detailed representation of the urban environment (e.g. buildings, roads, vegetation, etc.) that can be used e.g. for estimating noise propagation (Figure 2.2).

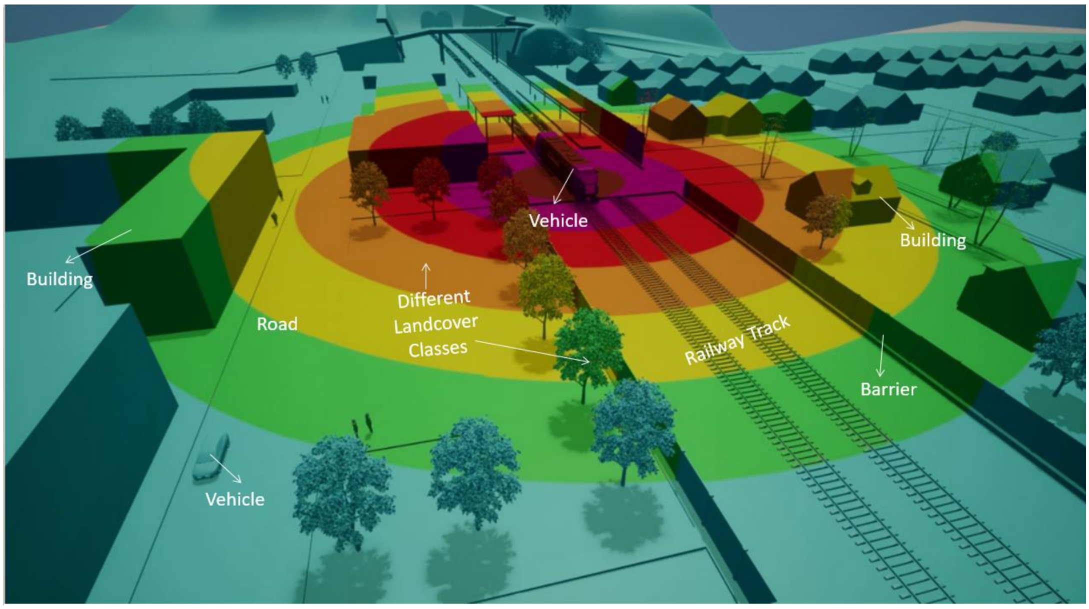

Figure 2.2 A 3DCM with the marked objects that affect city noise levels (modified from Stahre et al., 2021)

At the early stage, visualization seems to dominate the 3DCM application (Biljecki et al., 2015). Sinning-Meister et al. (1996) developed a user-friendly software environment for visualizing the design of an urban area in 3D, and various generation techniques were presented to improve the 3DCM visualization (Cohen & Manocha, 2005; Glander & Döllner, 2009). The increasing momentum of the construction of 3DCMs can be traced back to 2000 (Batty et al., 2001). With the improvement of the price/performance ratio in graphic computing (Delaney, 2000), large cities such as New York, Tokyo, and London started to construct their 3DCMs (Batty et al., 2001).

Later, simulation models were then developed for a very wide range of use cases and applications based on geometry, semantic information, domain-specific extensions, and external data (Ross, 2011). For instance, Beck (2003) mentioned the applications e.g. VRGIS, Cyber City Modeler as well as web plugins e.g. ViewTec for visualizing big 3DCMs in real-time. Kaden & Kolbe (2014) estimated the city-wide energy demands of buildings based on the 3DCM of Berlin as well as the enriched information from stakeholders and disciplines. Von Schwerin et al. (2013) developed a 3D Web GIS application QueryArch3D to allow researchers to analyze ancient architecture and landscapes.

To manage, exchange and interoperate 3DCM between applications and organizations, there is a requirement for standardizing 3DCM (Kolbe, 2009). Two standards are commonly used to solve these problems:

1) CityGML (Gröger & Plümer, 2012; Kolbe et al., 2021): It is based on XML and GML, focusing on the semantic objects, attributes, and relationships that are required by thematic queries and analyzes. For specific applications or use cases, CityGML provides a uniform mechanism called Application Domain Extensions (ADE) to extend the CityGML model. More information about CityGML will be described in Section 2.5.
2) CityJSON (Ledoux et al. 2019): CityJSON is a simplified CityGML model based on JSON format that is mostly used in Web GIS development. The main reason is that JSON is commonly used by APIs and for data exchange on the web. CityJSON also supports extensions to specific applications and use cases, which are defined as simple JSON files.

Many countries have developed national standards for 3DCM. Most of them are based on CityGML (Stoter et al., 2013; Gruber et al., 2014; van den Brink et al. 2013), which is further demonstrated in Section 2.5.

2.5 CityGML

CityGML is an open data model and XML-based format for the storage and exchange of virtual 3D city models. It is an application schema for the Geography Markup Language version 3.1.1 (GML3), the extendible international standard for spatial data exchange issued by the Open Geospatial Consortium (OGC) and the ISO TC 211. It defines the standard representation of basic entities, attributes, and relations of a 3DCM, which facilitates the application and sustainable maintenance of 3DCMs (Gröger et al., 2012). CityGML 3.0 conceptual model was accepted by OGC in 2021(Kolbe et al., 2021). It standardizes the underlying information themes based on the previous versions and allows the data encoding in GML/XML, and JSON as well as database schemas. Compared with the previous versions, CityGML 3.0 is better at representing indoor space in different LoDs and integrating with BIM (Kolbe et al., 2021).

2.5.1 CityGML 2.0

CityGML has been used since 2008, and an extended version of CityGML 2.0 has been adopted in 2012. In this study, we will only use CityGML 2.0 which the 3CIM (see Section 2.7) model is based on. The thematic themes of CityGML 2.0 are listed in Table 2.1.

Table 2.1 Thematic Themes in CityGML 2.0 (Gröger et al., 2012)

Thematic Themes	Description
CityGML core	The basic concepts and components of the overall CityGML data model (e.g. basic data types and thematic classes).
Digital Terrain (DTM)	The terrain model is specified as a regular raster, grid, TIN, break lines, or mass points, etc.
Bridge	The representation of thematic, spatial, and visual aspects of bridges and bridge parts
Building	The representation of thematic and spatial aspects of buildings and building parts.
City Furniture	The representation of immovable objects like lanterns, traffic lights, traffic signs, benches, and bus stops.
City Object Groups	A city object group aggregates city objects and furthermore defines them as a special city object.
Generic City Objects and Attributes	It allows the storage and exchange of 3D objects which are not covered by any other explicitly thematic themes within CityGML or which require attributes not represented in CityGML.
Land Use	The representation of both the way human uses the land parcels (e.g. settlement area) and the physical appearance of the land parcels (e.g. wetland).
Transportation Objects	A multi-functional, multi-scale theme focusing on thematic and functional as well as on geometrical/topological aspects of transportation features (e.g. roads, tracks, squares)
Tunnel	The representation of thematic and spatial aspects of tunnels and tunnel parts.
WaterBodies	The representation of the thematic aspects and 3D geometry of rivers, canals, lakes, and basins. In the 3CIM, artificial phenomena like dams and locks are also included.
Vegetation Objects	The representation of solitary vegetation objects and vegetation areas.

Apart from the thematic themes, CityGML 2.0 can be extended with an ADE. The ADE includes the additional information that needs to be modeled and exchanged in specific applications like noise simulation. . CityGML 2.0 also includes a code list, which is a list of suggestion values for specific attributes.

2.5.2 Levels of Detail

In practice, users often gather input data from various sources, which are represented in different Levels of Detail (LoDs). LoD0 represents a feature in 2.5D, which refers to a polygon, triangulation, raster, breaklines, or multi-points with height information embedded in a 3D space. LoD1 represents a volume object as a prismatic block with vertical walls and horizontal roofs. LoD2 includes simple structures for city objects. For instance, roof shapes, and dormers of buildings are represented. LoD3 includes more details for the outermost shape of objects. For instance, the bridges, tunnels, openings of buildings (e.g. windows, doors), and the shapes of vegetation are represented. LoD4 adds interior structures such as rooms (Figure 2.3) (Gröger & Plümer, 2012).

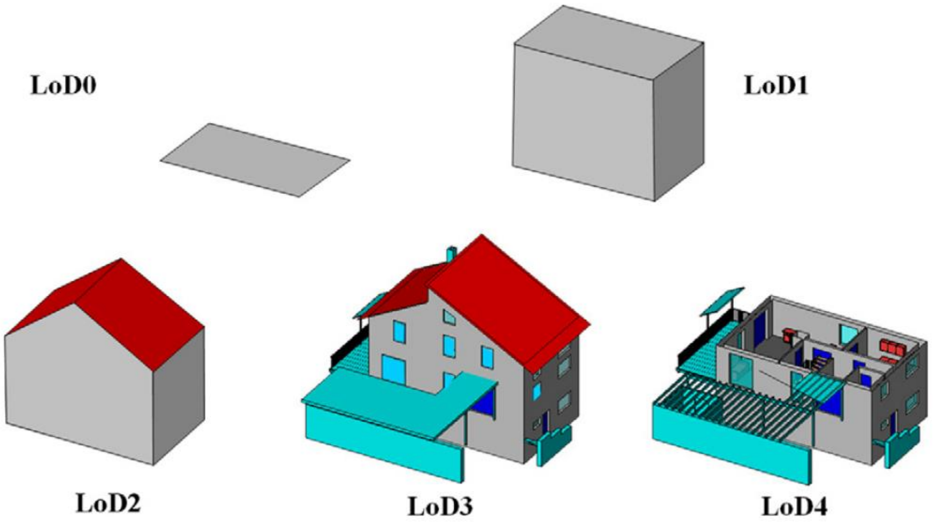

Figure 2.3. Buildings in five LoDs in CityGML 2.0 (Gröger & Plümer, 2012)

2.5.3 Application Domain Extension (ADE)

The ADE is a built-in mechanism of CityGML to augment its data model with additional concepts required by particular use cases. CityGML is a universal and application-independent model. This leads to the problem that the feature classes and attributes in CityGML may not fulfill the data requirement of a specific application or use case (Biljecki et al., 2018). For instance, in noise simulation models, the object segmentation of roads according to noise requirement and the attribute reflection of buildings are necessary for noise level calculation (Czerwinski et al., 2007a). The objects and attributes are not included in the CityGML file. Therefore, the ADE can be introduced to extend the CityGML schema for a specific application or use case and still maintain semantic interoperability (Kavisha et al., 2017). ADE involves extending the existing CityGML schema by adding new classes and object attributes (Czerwinski et al., 2007a). It is widely used in many domains, including energy simulation (Nouvel et al., 2015; Dalla Costa et al., 2011), heritage house management (Mohd et al., 2017), and air pollution monitoring (Arco et al., 2016), etc.

2.6 3CIM Model

In order to facilitate the connection and management of different municipalities, and different parts within the municipalities, the three main cities in Sweden - Stockholm, Gothenburg, and Malmö - together with Lund University developed the 3D City Information Model (3CIM) to store geographic information (Uggla et al. 2022). The current version of 3CIM is 1.0.

3CIM is based on CityGML 2.0 and has created extensions through ADE functionality for additional objects and attributes. 3CIM allows to store everything included in CityGML. However, there are some differences between CityGML and 3CIM: 1) 3CIM uses attribute classes and functions from CityGML but utilizes 3CIM's own code lists; 2) 3CIM removed the attribute *usage* from all themes. The thematic themes used in 3CIM are listed in Table 2.2. All information in 3CIM is stored in a SWEREF 99 planar coordinate system (e.g. SWEREEF 99 13 30) and in the height system RH 2000.

3CIM does not contain much attribute information. Instead, it is linked to external registers, and databases (Table 2.3) (e.g. road, building, environment) using unique IDs (Figure 2.4)

Table 2.2 Thematic Themes in 3CIM (3CIM_ver2)

Thematic Themes	**Description**
Bro (Bridge)	The representation of thematic, spatial, and visual aspects of bridges and bridge parts
Byggnad (Building)	The representation of thematic and spatial aspects of buildings and building parts.
Ledningsnät (Utility)	The representation of pipeline information and objects belonging to the pipeline networks.
Markdetaljer (CityFurniture)	The representation of immovable objects like lanterns, traffic lights, traffic signs, benches, and bus stops.
Marktäcke (LandUse)	The representation of both the way human uses the land parcels (e.g. settlement area) and the physical appearance of the land parcels (e.g. wetland).
Transport (Transportation)	A multi-functional, multi-scale theme focusing on thematic and functional as well as on geometrical/topological aspects of transportation features (e.g. roads, tracks, squares)
Tunnel	The representation of thematic and spatial aspects of tunnels and tunnel parts.
Undermarksförhållanden (Subsoil Conditions)	It contains the geotechnical information, the soil type map, and additional information describing how the soil is made up.
Vatten (WaterBody)	The representation of the thematic aspects and 3D geometry of rivers, canals, lakes, and basins. In the 3CIM, artificial phenomena like dams and locks are also included.
Vegetation	The representation of solitary vegetation objects and vegetation areas.

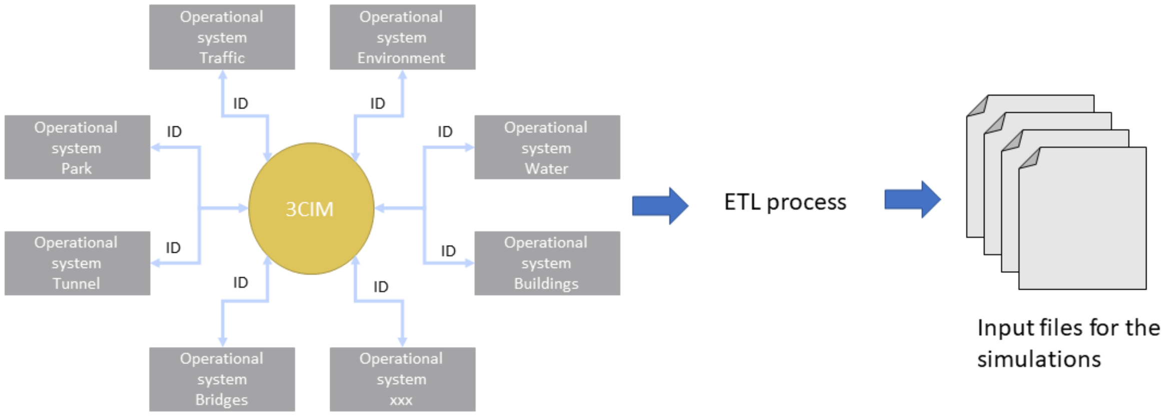

Figure 2.4. 3CIM data linked with external databases / operational systems (Uggla et al., 2022).

The 3CIM ADE encloses the information that is not covered in CityGML 2.0, for instance, the Utility theme and the status attribute of a Building Part object. In addition, 3CIM has its own code list (swe. *Kodlistor*) that is different from CityGML 2.0 code list.

Table 2.3 The connected external databases of 3CIM themes

Themes	External databases
Byggnad (Building)	3CIM acts as a refer body of the NS Byggnad[6] , which is the national specification for building objects developed by Lantmäteriet. For now, the *Building* theme in 3CIM follows the corresponding theme in CityGML 2.0 but with a few additions in terms of attributes.
Transport (Transportation)	The *Transport* theme is connected to NVDB/LVDB through segmentation and division of road surfaces.
Undermarksförhållanden	Waiting for the data from the State's Geotechnical Institute (SGI) and Sweden's Geotechnical Survey (SGU).

Some themes in 3CIM (e.g. Bridge, Building, and Tunnel) are represented in the LoDs that are the same as the corresponding themes in CityGML2.0. While the LoDs for other themes in 3CIM (e.g. Transportation, Vegetation) are different with the corresponding themes in CityGML2.0.

2.7 3D City Models in Noise Modeling

Big cities in many countries have developed 3D city models, where one application domain is to improve noise prediction at different heights (Law et al., 2011; Butler, 2004; Kavisha et al., 2017). Kavisha et al. (2017) argued that there is no better solution than CityGML (Gröger et al., 2012) to store and represent noise data. Additionally, the CityGML is also good as input for noise propagation. On the one hand, it combines the geometry model and semantic model for representing 3D city models, which allows the execution of complex queries and analyses in noise modeling (Stadler & Kolbe, 2007). On the other hand, CityGML can be extended using an ADE, which enables maintaining the 3D city model effectively while keeping semantic interoperability.

2.7.1 CityGML Noise ADE

As a member state of END, Germany was required to develop statewide and ubiquitous 3D geodata and thematic data (Czerwinski et al. 2007b). It was intended to provide very high-resolution 3D geodata for North Rhine-Westphalia (NRW), which is a city with a dense road network, a high amount of noise calculation areas as well as objects. Hence, a CityGML noise application schema based on the ADE mechanism was developed by the Institute of Geodesy and Geoinformation University of Bonn and the Special Interest Group SIG 3D of GDI NRW in Germany (Czerwinski et al. 2007b). New objects and noise attribute reflection of a building were supplied into the CityGML (Czerwinski et al. 2007b).

The *Transportation* module was extended by the object classes *NoiseRoadSegment* and *NoiseRailwaySegment*. Attributes like the reflection of buildings were introduced to an existing object class *_AbstractBuilding* of the *Building* module, while the *CityFurniture* module was extended by the object class *NoiseCityFurnitureSegment*. Each extended object class contains a set of attributes that are used for noise calculation. For instance, the traffic flow in the *NoiseRoadSegment* class and the height of city furniture in *NoiseCityFurnitureSegment* class (Gröger et al., 2012).

2.7.2 Development of the Noise ADE

There are some limitations in the original noise ADE. For instance, it has no information about noise barriers and no distinction in the speed of different vehicle types. Researchers in the Netherlands extended the original CityGML noise ADE by

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[6] NS Byggnad: https://www.lantmateriet.se/globalassets/smartare-samhallsbyggnadsprocess/nationella-specifikationer/natspec-dps-t-byggnad-version1.0-test4.pdf

introducing new feature types to meet the requirement (Kavisha et al., 2017). For instance, it introduced a new feature type *NoiseBarrier* to store the noise barrier information. In addition, it merged speed, traffic flow, and noise emissions with the existing noise attribute and then store these attributes for light as well as heavy vehicles separately (Kavisha et al., 2017).

2.8 Road and Traffic Datasets

A road dataset describes a road network and fundamental characteristics, referred to as features, linked to the network. Generally, it contains information about the name, classification, location, and traffic load of the roads. The road data support general mapping and GIS analysis for applications like traffic safety, noise simulation, and disaster planning.

CityGML has a theme *Transportation*. However, the main information source for road information is the road dataset. Either the city model has to be populated with information from the road dataset (requires a noise ADE) or one could link a road dataset to objects in the city model transport theme. The latter approach can be used in 3CIM (Figure 2.4).

Commissioned by Malmö stad, the road data used in this study is stored in Malmö Local Road Database (LVDB). The version used was last updated in October 2021. Attributes for the road dataset contain traffic load on different time slices, speed limit, name of roads, proportion of heavy vehicle, etc. The traffic count information was obtained by hose measurements during 2016-2021.

3 Case Study

3.1 Overview

The thesis aims to evaluate the capability of the municipality data (3CIM and traffic data) and elevation data (height model) from municipality to be used as input data in noise simulations. Section 3.2 describes the study area. Section 3.3 introduces original data sources, including the 3CIM data, road dataset and height model. Section 3.4 clarifies the reason behind selecting SoundPLAN as the noise simulation software. Section 3.5 interprets the methods to generate input data for noise simulations. Section 3.6 displays the input data generated in section 3.4. Section 3.7 clarifies the relationship between the attributes in the input data and the that was required in the noise simulation software. Section 3.8 shows the results generated from the noise simulation software.

3.2 Study Area

The study area is part of the city of Malmö in Skåne, south Sweden. It is centrally located not far from the Triangeln railway station and on the southwest of Pildammsparken (Figure 3.1). The study area is located around the junction of Lorensborgsgatan and Stadiongatan, including the east of the Solbacken, the west of Lorensborg, the east of Nya Bellevue, and the west of Ärtholmen. The main noise source in the study area is roads, and the receivers include residential buildings, schools as well as business buildings. Vegetation along the roads and between buildings provides a soft ground surface that could cause noise attenuation.

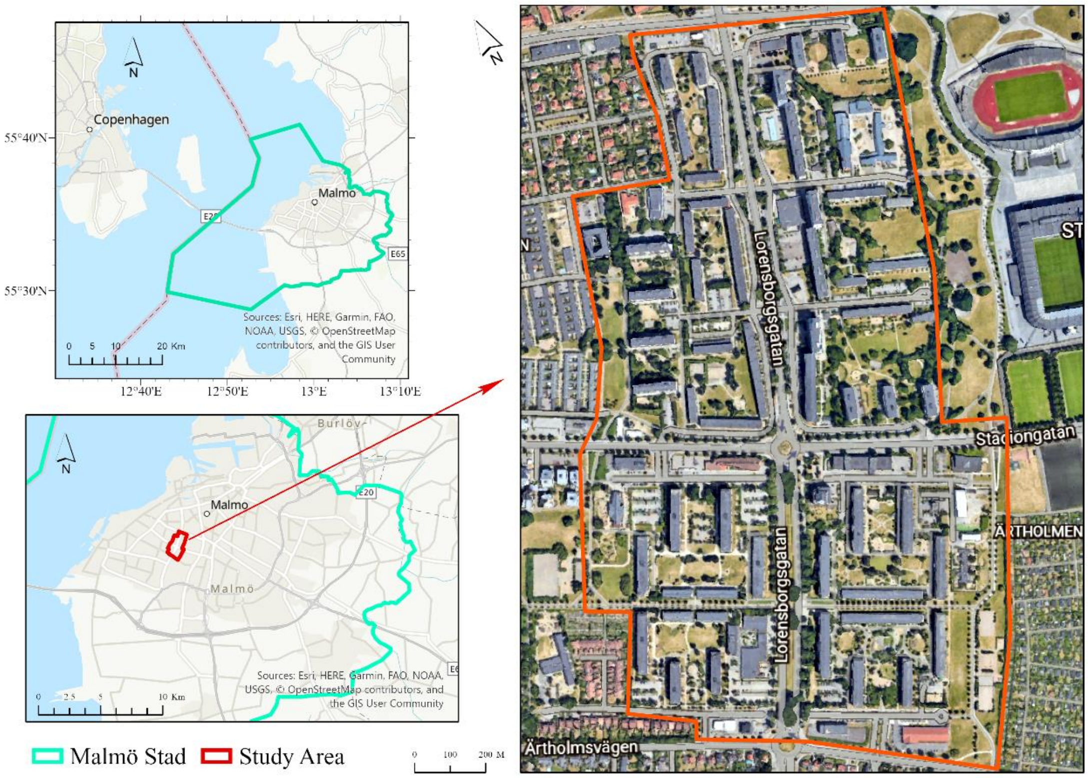

Figure 3.1 Study area in the city of Malmö.

(Source of Malmö Stad boundary: OpenStreetMap; Source of study area map: Google Earth)

3.3 Original Data

In noise simulation, the required data can be split into four parts: sources of noise, objects on propagation path, noise receivers, and height model (Kephalopoulos et al., 2012; SoundPLAN GmbH, 2019). The road dataset (Section 3.3.2) contains the sources of noise. Five object classes in 3CIM represent the objects on the noise propagation path (Section 3.3.1). A digital elevation model (DEM) is used as the height model (Section 3.3.3). The receiver set varies from calculation type. For instance, it could be generated based on building façades in Façade Noise Map or evenly distributed points in Grid Map. Therefore, the Building Part object class can be seen as receivers in the Façade Noise Map calculation. Figure 3.2 displays the use of part of the input data.

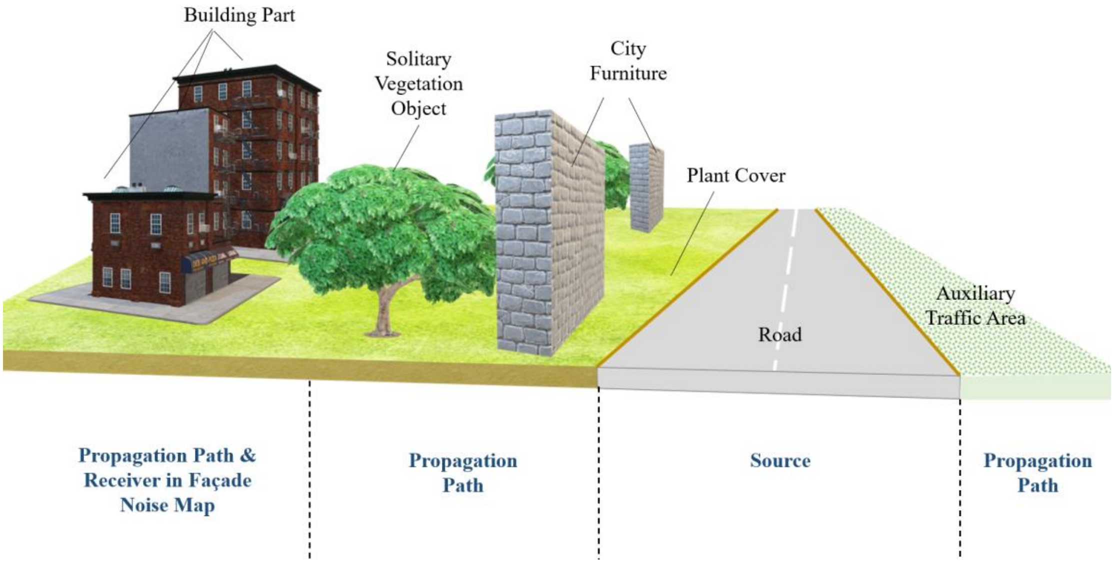

Figure 3.2 The use of input data (except height model)

3.3.1 3CIM data

The 3CIM data was provided by Malmö Stad, based on the SWEREF 99 13 30 (EPSG: 3008) reference system. Figure 3.3 gives an impression of the 3CIM data in the study area. It includes 10 thematic themes and the following five object classes in the themes are used:

Figure 3.3 The 3CIM data in the study area. Viewing from North-East (Uggla et al. 2022).

A) *Auxiliary Traffic Area*

Auxiliary Traffic Area is an object class in the *Transportation* theme in 3CIM. It describes the separation between lanes, for instance, drag way and middle lane. 3CIM contains the attribute of the separation surface material (*citygml_surface_material_codeSpace*), including asphalt, earth, grass, etc., Different surface materials mean ground surface with different sound attenuation factors on noise propagation path. In the *Transportation* theme, the code list of *Auxiliary Traffic Area* of surface material is in accordance with *Traffic Area* surface material (see Table II.1 in Appendix II). This sub-theme is stored in LoD2 as multi-surface, while each multi-surface has only one 3D polygon represented by a linear ring. Each node of a ring is a 3D point (x, y, z).

B) *City Furniture*

The *City Furniture* theme contains the city small objects such as bus shelter, wall, and terrain stairs. Since some types of city furniture like wall and retaining wall can prevent noise propagation, they should be taken into consideration as noise barriers on the propagation path. The functions of city furniture (*citygml_function{}.codeSpace*) follows the CityFurniture_function code list in 3CIM. Each city furniture is stored as a LoD1 geometry, which is a 3D linear ring or a polygon represented by a 3D linear ring.

C) *Solitary Vegetation Object*

The *Solitary Vegetation Object* is an object class in the *Vegetation* theme. It is linked with a local tree database (swe. *Lokala träddatabasen*), which stores the city vegetation including trees, shrubs, climbing plant, etc. The vegetation is able to reduce noise level, thus it is considered as the object on noise propagation path. Height of a vegetation object can be found in the local tree database. Other attributes like trunk diameter (*citygml_trunk_diameter*) and crown diameter (*citygml_crown_diameter*), and vegetation type (*trecim_geometry_metadata{}.trecim_lagesbestaminingsmetod_iplan_trecim_typ*) are stored in the 3CIM file. Each vegetation object is stored as a LoD2 geometry, which is represented by a 3D point.

D) *Plant Cover*

The *Plant Cover* is an object class in the *Vegetation* theme. It contains the land parcels covered by plants. The plant forms soft ground surface and increases the sound attenuation on the noise propagation path. The functions of plant (e.g. grass area, pasture, annual flower bed) are stored in the *citygml_function{}.codeSpace* attribute, which is in accordance with the *PlantCover_function* code list in 3CIM. The Plant Cover object is stored in LoD1 as multi-surface, while each multi-surface has only one 3D polygon represented by a linear ring.

E) *Building Part*

The *Building Part* is an object class in the *Building* theme. It represents a single building, which means a *Building* object consists of several *Building Part* objects (Figure 3.4). On the one hand, the building façades can be seen as noise protection objects on the propagation path. On the other hand, people living in a building are affected by environmental noise, thus the façades are used to generate receiver points in façade noise estimation. Each *Building Part* object is stored in LoD2 as solid or LoD3 as multi-surface. A solid or multi-surface is consisting of several 3D polygons that are the composite surfaces of a building, including wall surfaces and roof surfaces. Each 3D polygon is represented by a linear ring.

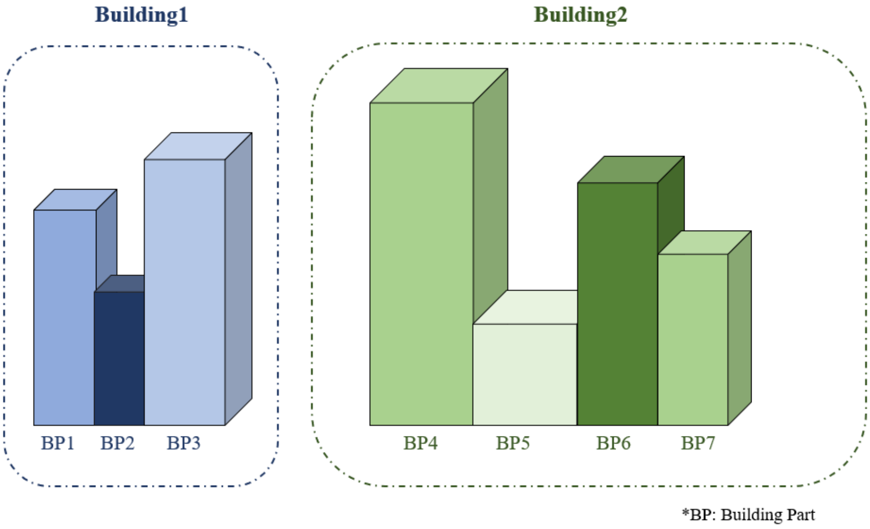

Figure 3.4 The relationship between Building and Building Part (BP).

3.3.2 Road Dataset

The road dataset was provided by Malmö Stad, which was linked with the local road database (swe. lokala vägdatabasen) and was last updated in October 2021. The reference system is SWEREF 99 13 30 (EPSG: 3008). Road data with information about traffic load is used to calculate sources in noise simulation. The road attributes used in this project and the descriptions are listed in Table 3.1. As is shown in Figure 3.5, each road section is represented as a separate feature, and the attributes are about the specific road section.

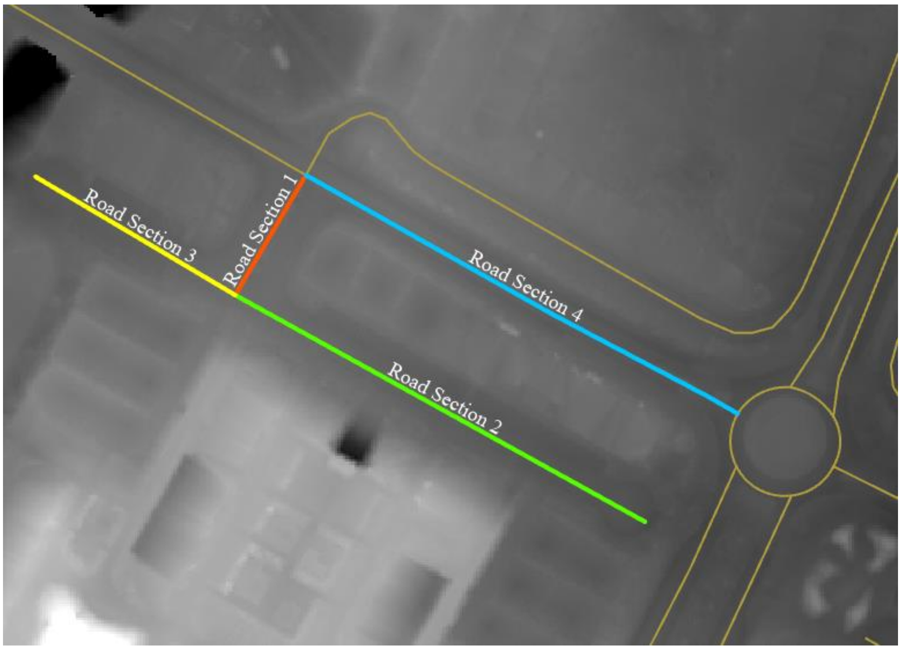

Figure 3.5 Four road sections in the road dataset

Table 3.1 Description of attributes from the road dataset that were used in noise calculation

Attribute	Description
GID	Unique ID
GK_IDVAG	Road network ID (2021)
NAMN	Road name (2021)
TYP_21	Road classification (2021)
TYP_NAMN	Road classification description
MVD_20	The average number of vehicles on a weekday, rounded to 100 (2020).
DAG_20	The number of vehicles at 6:00-18:00 on a weekday, estimated from MVD_20 with a factor of 0.76 then rounded to 10 (2020).
KVÄLL_20	The number of vehicles at 18:00-22:00 on a weekday, estimated from MVD_20 with a factor of 0.17 then rounded to 10 (2020).
NATT_20	The number of vehicles at 22:00-6:00 on a weekday, estimated from MVD_20 with a factor of 0.07 then rounded to 10 (2020).
TUNG_20	The proportion of heavy vehicles (2020)
HAST_21	Signed vehicle speed from NVDB in km/h (2021)

3.3.3 Height Model

The height model was provided by Malmö Stad, which is a Digital Elevation Model (DEM) stored in TIF format. It is based on the SWEREF 99 13 30 (EPSG: 3008) reference system and RH 2000 height system with a resolution of 1×1 m. The height model represents the terrain without overlaying objects (e.g. trees, buildings). It has been clipped to the study area, where the elevation ranges from 7.1 masl to 18.0 masl.

3.4 Selection of Software

As member state in the EU and thereby having to fulfill the European Noise Directive (END), Sweden needs to provide strategic noise maps to the Commission every five years. To harmonize and make the result from EU member states comparable, END provided the CNOSSOS-EU standard simulation method. SoundPLAN supports the CNOSSOS-EU standard when performing noise simulation. And the GmbH company provides the full access to SoundPLAN software during the master thesis project. That is why SoundPLAN software was selected for noise simulation in this study.

3.5 Methods to Generate Input Data to Simulations

When generating the input data, new attributes were added to road dataset and five object classes of the 3CIM data. The selection of attributes was based on the requirement of the noise simulation software SoundPLAN, which can be seen in section 3.7.

The generation of the input data was performed in the Extract Transform Load (ETL) tool Feature Manipulation Engine[7] (FME) from Safe software. The sections below describe which FME transformers that were utilized in the generation process (all in *italic* style). The FME scripts are available as open source on GitHub (Link for the FME scripts). An overview of the workflow is shown in Figure 3.6.

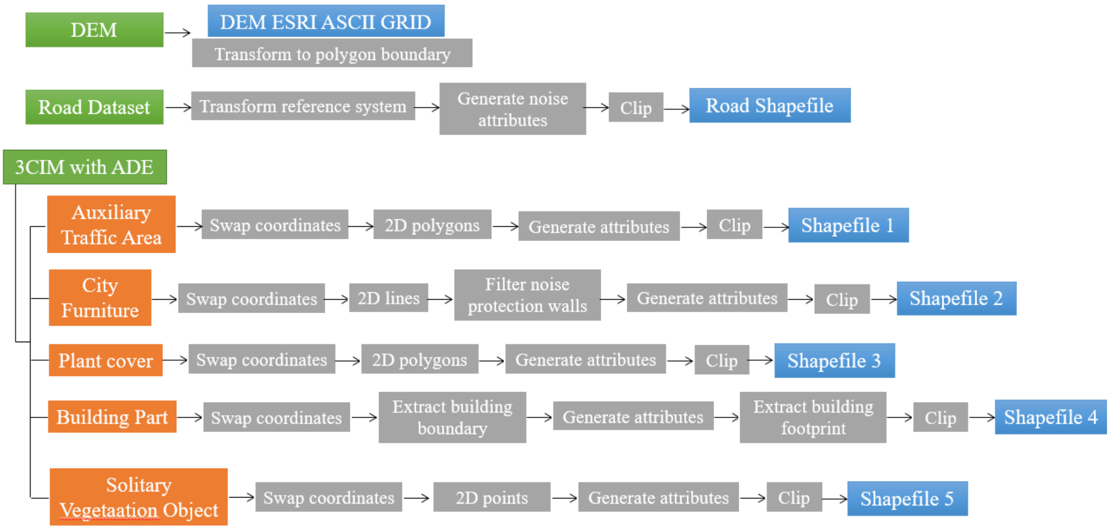

Figure 3.6 Workflow of preparing input data for noise simulation

3.5.1 DEM ASCII Grid

When calculating the noise levels in SoundPLAN, it is required that the extend of all input object types should be within the extent of digital ground model (DGM). Therefore, the DEM data was used as the DGM as well as the boundary of other input data. For preparing the DGM, DEM in Geotiff format was transformed into an ESRI ASCII GRID that is readable in SoundPLAN. The DGM was calculated based on the DEM in SoundPLAN by the *Calculate DGM* transformer.

For preparing the polygon boundary for other input data, firstly, all the cell value with valid height information was replaced by 1 while others were set to 0 by the *RasterCellReplacer* transformer. Then the new raster was transformed into a polygon boundary by the *RasterToPolygonCoercer*.

3.5.2 Road Shapefile Lines for noise sources

The geometry of road features in the original road dataset was the shapefile line. It can be imported as a noise source to the noise simulation software without converting the geometry directly. However, it was necessary to transform the spatial reference system

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[7] FME: https://www.safe.com/

of the road dataset to fit other data sources (e.g. 3CIM). Also, some required traffic attributes (e.g. hourly traffic load in specific time slices) need to be recalculated to improve the noise simulation accuracy.

1) Reference System Transformation

According to the metadata of the road dataset, it is based on SWEREF 99 13 30 reference system. However, when importing the road dataset to SoundPLAN, it was not at the same location as 3CIM and DEM data. Therefore, a *Reprojector* transformer was used to transform the spatial reference system from SWEREF 99 TM into SWEREF 99 13 30.

2) Traffic Noise Attributes Calculation

Noise attributes required in SoundPLAN were calculated based on the existing attributes of the road dataset (Table 3.2) by the *AttributeCreator* transformer. According to the CNOSSOS-EU standard, the day is 12 hours (7:00-19:00), the evening is four hours (19:00-23:00) and the night is eight hours (23:00-7:00), while the day, evening, and night are defined slightly differently at the national level (Kephalopoulos et al., 2012, Directive, E. U., 2002). In the original road dataset, the day is 6:00-18:00, the evening is 18:00-22:00, and the night is 22:00-6:00. All the traffic noise measurements are based on this time slice.

Table 3.2 Traffic noise attributes calculation

New Attribute	**Calculation Method**	**Note**
*veh_h_*d: The number of vehicles in each hour during daytime	= *DAG_20* / 12	*DAG_20*: number of vehicles during daytime
veh_h_e: The number of vehicles in each hour in the evening	= *KVÄLL_20* / 4	*KVÄLL_20*: number of vehicles in the evening
veh_h_n: The number of vehicles in each hour at night	= *NATT_20* / 8	*NATT_20*: number of vehicles at night
k_d: Hourly traffic during the daytime divided by Average Daily Traffic (ADT)	= *DAG_20* / 12 / *MVD_20*	*MVD_20*: The average number of vehicles on a weekday.
k_e: Hourly traffic in the evening divided by ADT	= *KVÄLL_20* / 4 / *MVD_20*	
k_n: Hourly traffic at night divided by ADT	= *NATT_20* / 8 / *MVD_20*	
speed_d: Vehicle speed during daytime in km/h	= *HAST_21*	*HAST_21*: Signed vehicle speed in km/h
speed_e: Vehicle speed in the evening in km/h	= *HAST_21*	
speed_n: Vehicle speed at night in km/h	= *HAST_21*	

3) Data Clip and Output as Shapefile Lines

The road dataset was clipped by the polygon boundary (see Section 3.6.1) with the *Clipper* tool. If a part of a road feature is out of the extent, the whole road feature will be rejected. After clipping, the valid roads were output as shapefile lines by the *Writer* transformer.

3.5.3 Auxiliary Traffic Area Shapefile Polygons

The geometry of *AuxiliaryTrafficArea* object class was 3D polygon (see section 3.3.1). To import the data into noise simulation software, the geometry was transformed into 2D shapefile polygon. In addition, the coordinates of each object need to be swapped (reverse the input latitude and longitude coordinates) to fit other data (e.g. road dataset). Some noise attributes need to be added to make it readable in noise simulation software and improve the simulation accuracy.

1) Data Reading, Coordinate Transformation, and 2D Data Extraction

The *Auxiliary Traffic Area* object class of 3CIM data was read in CityGML 2.0 format. The x, y coordinates of 3CIM objects are opposite to those of the DEM and road dataset. Thus, the *CoordinateSwapper*[8] transformer was used for getting the correct x, y coordinates. The objects of the *Auxiliary Traffic Area* were represented by 3D polygons, which were then transformed into 2D polygons by a *2DForcer*.

2) New ID and Attributes Generation

In 3CIM, the unique identifier for each object was stored in the *gml_id* field. However, the data format of *gml_id* was the character, which was not readable as an object ID in SoundPLAN. Therefore, a *Counter* tool generated a serial integer ID for each object from zero and stored it in a new attribute field *id*. The second new attribute was ground class based on CNOSSOS standard (*cnossos_cla*). It was a reclassification of the original surface material in accordance with the CNOSSOS ground classification. The CNOSSOS ground class represents ground surfaces with different hardness by letters A-H. The third new attribute (*ground_fac*) was the corresponding ground factor for each ground class in accordance with the CNOSSOS standard (Table 3.3). Each ground class has a specific ground factor with the range of 0-1, which measures the ground acoustic absorption ability in noise simulation (Kephalopoulos et al., 2012).

Table 3.3 Reclassification of ground classes and the corresponding ground factors for *AuxiliaryTrafficArea* object class

Surface material code space in 3CIM (*citygml_surface_material_codeSpace*)	**Description of surface material in 3CIM**	**Ground class in CNOSSOS**	**Ground factor in CNOSSOS**
10000	Asphalt	G	0
10001	Concrete/Betong	G	0
10009	Grass/Gräs	C	1

3) Data Clip and Output as Shapefile Polygons

After generating new attribute fields, the *Auxiliary Traffic Area* was clipped by the polygon boundary (see Section 3.5.1) with the *Clipper* tool. If a part of a feature is out of the extent, the whole feature will be rejected, due to the parts outside the DGM extent will cause error when calculating noise level in SoundPLAN. The valid features were output as shapefile polygons by *Writer*. Attribute *cnossos_cla* was renamed as *gr_cla*.

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[8] *CoordinateSwapper*: https://docs.safe.com/fme/html/FME_Desktop_Documentation/FME_Transformers/Transformers/coordinateswapper.htm

3.5.4 City Furniture Shapefile Lines

The geometry of *CityFurniture* object class was 3D linear ring or 3D polygon (see section 3.3.1). To import the data into noise simulation software, the geometry was transformed into 2D shapefile line. In addition, the coordinates of each object need to be swapped to fit other data (e.g. road dataset). Some noise attributes need to be added to make it readable in noise simulation software and improve the simulation accuracy.

1) Data Reading, Coordinate Swap, and 2D Data Extraction

The *City Furniture* object class of 3CIM data was read in CityGML 2.0 format. The *CoordinateSwapper* tool was used for getting the correct x, y coordinates. The objects of the *City Furniture* were represented by 3D polygons or 3D line strings, but all of them were then transformed into 2D line strings by a *2DForcer*.

2) New ID Generation

Due to the original gml_id being a character type field and being unreadable in SoundPLAN, a *Counter* tool generated an integer ID for each object from zero and stored it in a new attribute field *id*.

3) City Furniture Filtering

The objects of City Furniture had various functions, including wall, retaining wall, fence, etc. 3CIM had a code list for the city furniture function, which was stored in the *citygml_function{0}.codeSpace* attribute field. Wall and Retaining Wall were represented by values 51100 and 60100 respectively. A *TestFilter* transformer was used to filter the City Furniture objects, only the walls and the retaining walls were kept for further calculation.

4) New Attributes Generation

The first attribute was the height of city furniture in meters (*height*). Due to the original data having no height information, all walls were set to 1m, and retaining walls were set to 0.5m. The second attribute was the city furniture floats above ground in meters (*abov_gr*), which was also unavailable in the original data and was set to 0m.

3) Data Clip and Output as Shapefile Lines

The *City Furniture* was clipped by the polygon boundary (see Section 3.5.1) with the *Clipper* transformer. If a part of a feature is out of the extent, the whole feature will be rejected. The valid features were output as shapefile lines by *Writer*. When setting *Writer* parameters, the output Geometry must be shapefile line. If not, the *Writer* transformer could only output the city furniture represented by polygons.

3.5.5 Plant Cover Shapefile Polygons

The geometry of *PlantCover* object class was 3D polygon (see section 3.3.1). To import the data into noise simulation software, the geometry was transformed into 2D shapefile polygon. In addition, the coordinates of each object need to be swapped to fit other data (e.g. road dataset). Some noise attributes need to be added to make it readable in noise simulation software and improve the simulation accuracy.

1) Data Reading, Coordinate Swap, and 2D Data Extraction

The *Plant Cover* object class of 3CIM data was read in CityGML 2.0 format. The *CoordinateSwapper* transformer was used for getting the correct x, y coordinates. The objects of the *Plant Cover* were represented by 3D polygons, which were then transformed into 2D polygons by a *2DForcer*.

2) New ID and Attributes Generation

The first new attribute field was the integer *id* generated by the *Counter* transformer. The second new attribute was ground class based on CNOSSOS standard (*cnossos_cla*). It was a reclassification of the original function in accordance with the CNOSSOS ground classification. The third new attribute (*ground_fac*) was the corresponding ground factor for each ground class in accordance with the CNOSSOS standard (Table 3.4). The description of the ground class and ground factor attributes is the same as that in Section 3.6.3, but the *Plant Cover* function had its own code list.

Table 3.4 Reclassification of ground classes and the corresponding ground factors for *PlantCover* object class

Function code space in 3CIM (*citygml_function{0}.codeSpace*)	**Description of function in 3CIM**	**Ground class in CNOSSOS**	**Ground factor in CNOSSOS**
10100	Grass area/Gräsyta	C	1
10200	Planting/Plantering	D	1

3) Data Clip and Output as Shapefile Polygons

After generating new attribute fields, the *Plant Cover* was clipped by the polygon boundary (see Section 3.5.1) with the *Clipper* tool. If a part of a feature is out of the extent, the whole feature will be rejected. The valid features were output as shapefile polygons by *Writer*. Attribute *cnossos_cla* was renamed as *gr_cla*.

3.5.6 Building Part Shapefile Polygons

The geometry of *BuildingPart* object class was 3D solid (see section 3.3.1). To import the data into noise simulation software, the footprint of each object was extract as a 2D shapefile polygon. Building height was recalculated and added as an attribute. In addition, the coordinates of each object need to be transformed to fit other data (e.g. road dataset). All the work was performed in FME and below it is stated which FME transformers that were used.

1) Data Reading, Coordinate Transformation, and Building Boundary Extraction

The *Building Part* object class of 3CIM data was read in CityGML 2.0 format. The *CoordinateSwapper* tool was used for getting the correct x, y coordinates. The objects of the *Building Part* were represented by solids. A *BoundsExtractor* tool was used to obtain the minimum and maximum height (*_zmin*, *_zmax*) of each building object.

2) New ID and Attributes Generation

The first new attribute field was the integer *id* generated by the *Counter* tool. The second new attribute is the building height in meters calculated from the height of building bounds (*height* = *_zmax* - *_zmin*).

3) Building Footprint Extraction, Data Clip, and Output as Shapefile Polygons

Although SoundPLAN support importing Building in CityGML 2.0 format, the 3CIM Building Part is not readable even output as a CityGML file. Thus, it was transformed into 2D polygons by the *SurfaceFootprintReplacer* transformer. Then *Building Part* was clipped by the polygon boundary (see Section 3.5.1) with the *Clipper* tool. If a part of a feature is out of the extent, the whole feature will be rejected. The valid features were output as shapefile polygons by the FME transformer *Writer*.

3.5.7 Solitary Vegetation Object Shapefile Points

The geometry of *PlantCover* object class was 3D point (see section 3.3.1). To import the data into noise simulation software, the geometry was transformed into 2D shapefile point. In addition, the coordinates of each object need to be swapped to fit other data (e.g. road dataset). Some noise attributes need to be added to make it readable in noise simulation software and improve the simulation accuracy.

1) Data Reading, Coordinate Swap, and 2D Data Extraction

The *Solitary Vegetation Object* object class of 3CIM data was read in CityGML 2.0 format. The *CoordinateSwapper* tool was used for getting the correct x, y coordinates. The objects of the *Solitary Vegetation Object* were represented by 3D points, which were then transformed into 2D points by a *2DForcer* transformer.

2) New ID and Attributes Generation

The first new attribute field was the integer *id* generated by the *Counter* transformer. The second new attribute is the tree height in meters (*height*). All values were set to 2.5m and users can modify the value once obtaining the exact tree height.

3) Data Clip and Output as Shapefile Points

The *Solitary Vegetation Object* was clipped by the polygon boundary (see Section 3.5.1) with the *Clipper* transformer. If a part of a feature is out of the extent, the whole feature will be rejected. The valid features were output as shapefile points by *Writer*.

3.6 Input Data to Simulations

3.6.1 Height Model (DEM)

The height model in ESRI ASCII GRID format was imported as the elevation point object class. By executing the file, a Geo file of digital ground model (DGM) can be generated by SoundPLAN. This DGM will be used to evaluate the terrain of the study area in noise simulation.

3.6.2 Road Dataset

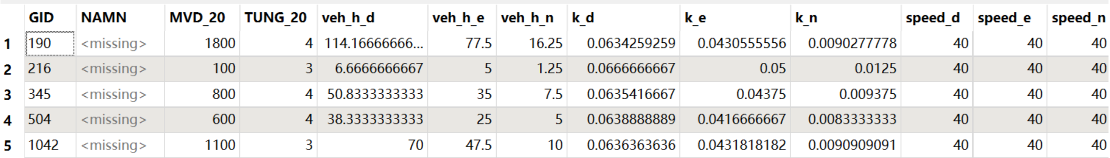
Referenct System: SWEREF99 13 30 TM
(EPSG: 3008)
Data Source: 3CIM Data from Malmö Stad.
Road Database from LVDB

Figure 3.7 Input Road data and 3CIM data

Figure 3.7 displays the input road data in a map. There were 11,616 road features in the Road shapefile, all of which were 2D lines. And 76 of the features were covered by the study area. The road shapefile contains 13 attributes (Table 3.6). An example of the shapefile attribute table was shown in Figure 3.8.

Table 3.5 Attributes information of Road shapefile

Attribute	Data type	Width	Precision	Description
GID	varchar	100		
NAMN	varchar	100		
MVD_20	number (double)		0	Traffic load
TUNG_20	number (double)		0	Heavy vehicle proportion
veh_h_d	number (double)		0	Traffic load
veh_h_e	number (double)		0	Traffic load
veh_h_n	number (double)		0	Traffic load
k_d	number (double)		0	Hourly traffic / ADT
k_e	number (double)		0	Hourly traffic / ADT
k_n	number (double)		0	Hourly traffic / ADT
speed_d	number (double)		0	Traffic speed
speed_e	number (double)		0	Traffic speed
speed_n	number (double)		0	Traffic speed



	GID	NAMN	MVD_20	TUNG_20	veh_h_d	veh_h_e	veh_h_n	k_d	k_e	k_n	speed_d	speed_e	speed_n
1	190	<missing>	1800	4	114.16666666...	77.5	16.25	0.0634259259	0.0430555556	0.0090277778	40	40	40
2	216	<missing>	100	3	6.6666666667	5	1.25	0.0666666667	0.05	0.0125	40	40	40
3	345	<missing>	800	4	50.8333333333	35	7.5	0.0635416667	0.04375	0.009375	40	40	40
4	504	<missing>	600	4	38.3333333333	25	5	0.0638888889	0.0416666667	0.0083333333	40	40	40
5	1042	<missing>	1100	3	70	47.5	10	0.0636363636	0.0431818182	0.0090909091	40	40	40

Figure 3.8 An example of the Road shapefile attribute table

3.6.3 3CIM data

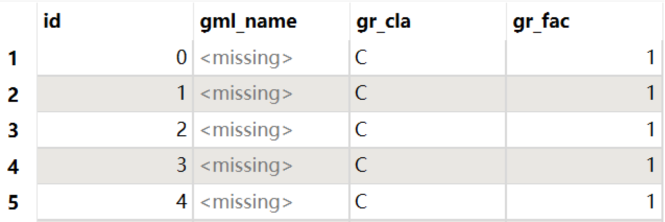
This section describes the 3CIM object classes after transformation. Figure 3.7 gives an overview of all shapefiles transformed from the five 3CIM object classes. Information for five transformed shapefiles was descript in the following sub-sections respectively.

Auxiliary Traffic Area Shapefile

There were 86 objects in the *AuxiliaryTrafficArea* object class of 3CIM data, which were all transformed to 2D polygons as a shapefile. Nodes of the transformed polygons kept the northing and easting, while the height was abandoned. The shapefile data contains four attributes (Table 3.6). An example of the shapefile attribute table was shown in Figure 3.9.

Table 3.6 Attributes information of Auxiliary Traffic Area shapefile

Attribute	Data type	Width	Precision	Description
id	number	10	0	
gml_name	varchar	254		
gr_cla	varchar	20		Ground class
gr_fac	number	20	10	Ground factor



	id	gml_name	gr_cla	gr_fac
1	0	<missing>	C	1
2	1	<missing>	C	1
3	2	<missing>	C	1
4	3	<missing>	C	1
5	4	<missing>	C	1

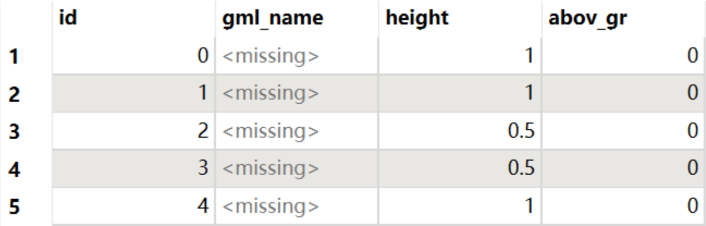
Figure 3.9 An example of the Auxiliary Traffic Area shapefile attribute table

City Furniture Shapefile

There were 329 objects in the *CityFurniture* object class of 3CIM data, two of which were 3D polygons and the rest were 3D linear strings. After filtering the wall and retaining wall, 211 objects were kept including the two polygon objects. All 211 objects were transformed into 2D shapefile lines, while the two polygons were transformed into end-to-end line strings. The shapefile data contains four attributes (Table 3.7). An example of the shapefile attribute table was shown in Figure 3.10.

Table 3.7 Attributes information of City Furniture shapefile

Attribute	Data type	Width	Precision	Description
id	number	10	0	
gml_name	varchar	254		
height	number	20	10	Wall height (m)
abov_gr	number	20	10	Height above ground (m)



	id	gml_name	height	abov_gr
1	0	<missing>	1	0
2	1	<missing>	1	0
3	2	<missing>	0.5	0
4	3	<missing>	0.5	0
5	4	<missing>	1	0

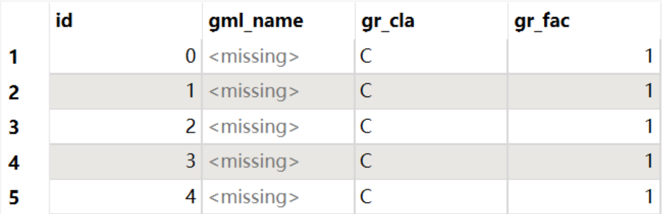
Figure 3.10 An example of the City Furniture shapefile attribute table

Plant Cover Shapefile

There were 124 objects in the *PlantCover* object class of 3CIM data, which were all transformed into 2D polygons as a shapefile. Nodes of the transformed polygons kept the northing and easting, while the height was abandoned. The shapefile data contains four attributes (Table 3.8). An example of the shapefile attribute table was shown in Figure 3.11.

Table 3.8 Attributes information of Plant Cover shapefile

Attribute	Data type	Width	Precision	Description
id	number	10	0	
gml_name	varchar	254		
gr_cla	varchar	20		Ground class
gr_fac	number	20	10	Ground factor



	id	gml_name	gr_cla	gr_fac
1	0	<missing>	C	1
2	1	<missing>	C	1
3	2	<missing>	C	1
4	3	<missing>	C	1
5	4	<missing>	C	1

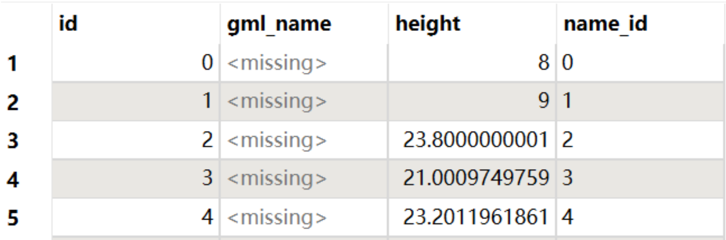
Figure 3.11 An example of the Plant Cover shapefile attribute table

Building Part Shapefile

The *BuildingPart* object class in 3CIM data contains 420 3D solid objects that were replaced by 2D surface footprints. Nodes of the 2D footprint kept northing and easting. The building height was calculated from solid geometry and was stored in an attribute field (*height*). There were 216 building part objects covered by the study area, which were kept in the final Building Part 2D polygon shapefile. The shapefile data contains four attributes (Table 3.9). An example of the shapefile attribute table was shown in Figure 3.12.

Table 3.9 Attributes information of Building Part shapefile

Attribute	Data type	Width	Precision	Description
id	number	10	0	
gml_name	varchar	254		
height	number	20	10	Building height (m)
name_id	varchar	254		Copy from id



	id	gml_name	height	name_id
1	0	<missing>	8	0
2	1	<missing>	9	1
3	2	<missing>	23.8000000001	2
4	3	<missing>	21.0009749759	3
5	4	<missing>	23.2011961861	4

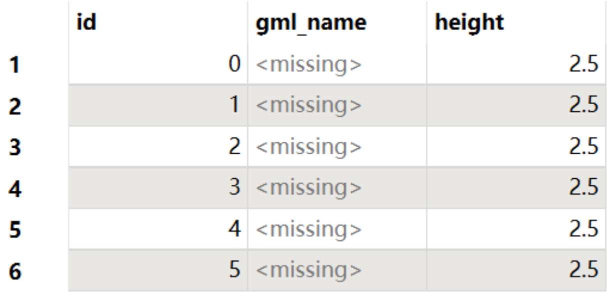
Figure 3.12 An example of the Building Part shapefile attribute table

Solitary Vegetation Object Shapefile

The SolitaryVegetationObject object class in 3CIM contains 2176 3D point objects, which were transformed into 2D points. Each point kept the northing and easting, while the height was abandoned. One of the 2176 points was not covered by the study area, and the remaining 2175 points were stored in the final 2D point shapefile. The shapefile data contains three attributes (Table 3.10). An example of the shapefile attribute table was shown in Figure 3.13.

Table 3.10 Attributes information of Solitary Vegetation Object shapefile

Attribute	Data type	Width	Precision	Description
id	number	10	0	
gml_name	varchar	254		
height	number	20	10	Tree height (m)



	id	gml_name	height
1	0	<missing>	2.5
2	1	<missing>	2.5
3	2	<missing>	2.5
4	3	<missing>	2.5
5	4	<missing>	2.5
6	5	<missing>	2.5

Figure 3.13 An example of the Solitary Vegetation Object shapefile attribute table

3.7 Mapping attributes in SoundPLAN

This section introduces the relationship between the attributes required by SoundPLAN and the attributes in the input data. First, the SoundPLAN required attributes are described in section 3.7.1. Then, in section 3.7.2 the one-to-one relationship between attributes from input data and SoundPLAN requirement are listed.

3.7.1 Required Parameters in SoundPLAN

The input data can be split into four categories:

1) Source of noise, which is the Road object type in SoundPLAN;
2) Objects on noise propagation path, which is consist of four object types in SoundPLAN: Noise protection wall, Ground absorption area, Tree, and Building;
3) Receiver, which is the Building object type;
4) Height model, which is the object type named Elevation point.

This section lists the mandatory parameters for road (Table 3.11), noise protection wall (Table 3.12), ground absorption area (Table 3.13), tree (Table 3.14), building (Table 3.15), elevation point (Table 3.16) object types and the parameters that are enclosed in the input data or can be calculated from the input data.

Table 3.11 Description of parameters in Road object type (CNOSSOS-EU Road 2015)

Attribute	Description
Name	Name of road object
ADT [Veh/24h]	Average Daily Traffic (Average number of vehicles in 24h)
Veh/h(d) (1-light moter vehicles)	The number of vehicles in each hour during daytime (6:00-18:00)
Veh/h(e) (1-light moter vehicles)	The number of vehicles in each hour in the evening (18:00-22:00)
Veh/h(n) (1-light moter vehicles)	The number of vehicles in each hour at night (22:00-6:00)
k(d)	Hourly traffic during the daytime (6:00-18:00) divided by ADT
k(e)	Hourly traffic in the evening (18:00-22:00) divided by ADT
k(n)	Hourly traffic at night (22:00-6:00) divided by ADT
p24[%] (3-heavy vehicles)	The percentage of heavy vehicles in 24h
Speed cat 1 (d) [km/h]	Vehicle speed during daytime (6:00-18:00) in km/h
Speed cat 1 (e) [km/h]	Vehicle speed in the evening (18:00-22:00) in km/h
Speed cat 1 (n) [km/h]	Vehicle speed at night (22:00-6:00) in km/h
ID	Unique ID of a road object

Table 3.12 Description of parameters in Noise protection wall object type

Attribute	Description
Name	Name of the wall
Wall height (m)	Distance between the bottom and top of the wall
Wall floats above ground	Distance between the ground surface and the bottom of the wall
ID	Unique ID of a wall object

Table 3.13 Description of parameters in Ground absorption area object type

Attribute	Description
Graphic object ID	Unique ID of a ground absorption area
Name	Name of the ground absorption area
Ground factor	The acoustic absorption factor of the ground surface
Ground class	Type of ground surface

Table 3.14 Description of parameters in Tree object type

Attribute	Description
Graphic object ID	Unique ID of a tree
Tree height	Height of a tree object

Table 3.15 Description of parameters in Building object type

Attribute	Description
Building type	The function of a building object (e.g. school, hospital)
Name	Name of a building object
ID	Unique ID of a building object
Building height [m]	Building height in meter

Table 3.16 Description of parameters in Elevation point object type

Attribute	Description
H1	Elevation of a point
Graphic object ID	Unique ID of a point

3.7.2 Mapping Attributes between Input Data and SoundPLAN

The transformed data were imported into SoundPLAN and generated an individual Geo-File for each file. The DEM ASCII GRID was imported as the elevation point and a Digital Ground Model (DGM) was executed in SoundPLAN. Others were all imported in ESRI Shapefile format. The *Road Dataset* was imported as Road; *Auxiliary Traffic Area* and *Plant Cover* as Ground Absorption Area; *City Furniture* as Noise Protection Wall; *Solitary Vegetation Object* as Tree; and *Building Part* as Building. When importing the object types, the users need to map attribute names in input data to the parameter names in SoundPLAN manually. The corresponding attribute names and parameter names are listed in Table 3.17.

Table 3.17 Corresponding attribute names in input data and parameter names in SoundPLAN

Input data	Attribute name (input data)	Parameter name (SoundPLAN)
Road	GID	Graphic object ID
	NAMN	Name
	MVD_20	ADT [Veh/24h]
	TUNG_20	p24[%] (3 – Heavy vehicles) [%]
	veh_h_d	Veh/h(d) (1-light moter vehicles)
	veh_h_e	Veh/h(e) (1-light moter vehicles)
	veh_h_n	Veh/h(n) (1-light moter vehicles)
	k_d	k(d)
	k_e	k(e)
	k_n	k(n)
	speed_d	Speed cat 1 (d) [km/h]
	speed_e	Speed cat 1 (e) [km/h]
	speed_n	Speed cat 1 (n) [km/h]
Auxiliary Traffic Area	id	Graphic object ID
	gml_name	Name
	gr_cla	Ground class
	gr_fac	Ground factor
Plant Cover	id	Graphic object ID
	gml_name	Name
	gr_cla	Ground class
	gr_fac	Ground factor
City Furniture	id	Graphic object ID
	gml_name	Name
	height	Wall height [m]
	abov_gr	Wall floats above ground
Solitary Vegetation Object	id	Graphic object ID
	height	Tree height [m]
Building Part	id	Graphic object ID
	name_id	Name
	height	Building height [m]

3.8 Results of the Noise Simulations

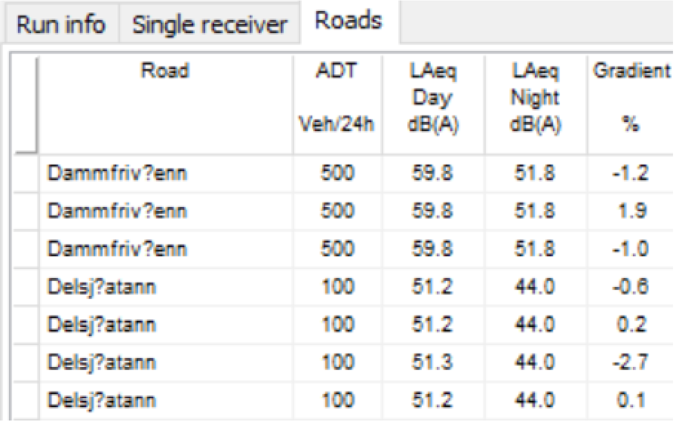
3.8.1 Noise Level Rendering Display

After importing the data, users can set the standards and assessment in SoundPLAN. In this case, CNOSSOS-EU standard, and noise indicator L_{den} were selected. Noise simulation was accomplished in the SoundPLAN calculation kernel. Figure 3.14 display a façade noise map that is an example of noise mapping. For saving program running time, the parameters such as reflection order (1) and maximum search (800 m) were set as low values. The noise levels in Figure 3.14 probably therefore to some extent underestimate the noise levels.

Figure 3.14 Façade noise map with roads and buildings for the study area (data to the simulations was only used for the study area and therefore the estimated noise levels in the border regions are not correct)

3.8.2 Noise Emission Statistics

Figure 3.15 is a screenshot of the road noise emission table. Each row represents a road feature. The rows with the same road names are different road features with different id. In this noise emission table, ADT refers to the average daily traffic load; L_{AeqDay}, $L_{AeqNight}$ (A-weighted equivalent sound pressure level) refers to the noise emission at a specific road at three time-slices of a day; and Gradient is the slope of a road. Users can also select and display other parameters such as traffic speed in the table setting.



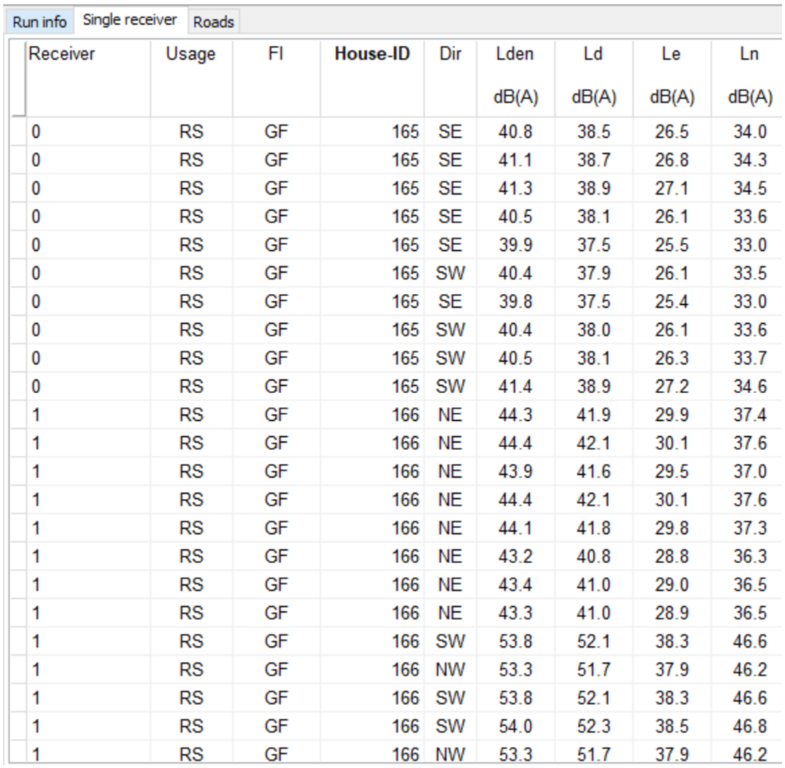
Road	ADT Veh/24h	LAeq Day dB(A)	LAeq Night dB(A)	Gradient %
Dammfriv?enn	500	59.8	51.8	-1.2
Dammfriv?enn	500	59.8	51.8	1.9
Dammfriv?enn	500	59.8	51.8	-1.0
Delsj?atann	100	51.2	44.0	-0.6
Delsj?atann	100	51.2	44.0	0.2
Delsj?atann	100	51.3	44.0	-2.7
Delsj?atann	100	51.2	44.0	0.1

Figure 3.15 Result table for road noise emission statistics

3.8.3 Single Receiver Noise Level Statistics

Figure 3.16 is a screenshot of the road noise emission table. 10919 receivers were successfully generated from the 216 input buildings. 99 receivers failed to be generated, due to the fact that one was outside the DGM area (which limits the study area) and the rest 98 receivers were inside of the assigned buildings.

Receiver refers to the receiver names generated by SoundPLAN; Usage is the area usage, here all buildings were set to residential buildings due to that there was no information about the usage (could possibly also be schools, hospitals, etc.); Fl indicates which floor a receiver was located on. In Figure 4.3 the receivers were on the ground floor (GF); House-ID is the object-ID of the assigned building that is the same as the *name_id* field of the input data; Dir indicates the direction of the building façade that the receiver was assigned. L_{den} is the day-evening-night noise level; L_d, L_e, and L_n are day, evening, and night noise levels respectively (see Section 2.2.4). Users can also select and display other parameters such as the receiver coordinates in the table setting.



Receiver	Usage	Fl	**House-ID**	Dir	Lden dB(A)	Ld dB(A)	Le dB(A)	Ln dB(A)
0	RS	GF	165	SE	40.8	38.5	26.5	34.0
0	RS	GF	165	SE	41.1	38.7	26.8	34.3
0	RS	GF	165	SE	41.3	38.9	27.1	34.5
0	RS	GF	165	SE	40.5	38.1	26.1	33.6
0	RS	GF	165	SE	39.9	37.5	25.5	33.0
0	RS	GF	165	SW	40.4	37.9	26.1	33.5
0	RS	GF	165	SE	39.8	37.5	25.4	33.0
0	RS	GF	165	SW	40.4	38.0	26.1	33.6
0	RS	GF	165	SW	40.5	38.1	26.3	33.7
0	RS	GF	165	SW	41.4	38.9	27.2	34.6
1	RS	GF	166	NE	44.3	41.9	29.9	37.4
1	RS	GF	166	NE	44.4	42.1	30.1	37.6
1	RS	GF	166	NE	43.9	41.6	29.5	37.0
1	RS	GF	166	NE	44.4	42.1	30.1	37.6
1	RS	GF	166	NE	44.1	41.8	29.8	37.3
1	RS	GF	166	NE	43.2	40.8	28.8	36.3
1	RS	GF	166	NE	43.4	41.0	29.0	36.5
1	RS	GF	166	NE	43.3	41.0	28.9	36.5
1	RS	GF	166	SW	53.8	52.1	38.3	46.6
1	RS	GF	166	NW	53.3	51.7	37.9	46.2
1	RS	GF	166	SW	53.8	52.1	38.3	46.6
1	RS	GF	166	SW	54.0	52.3	38.5	46.8
1	RS	GF	166	NW	53.3	51.7	37.9	46.2

Figure 3.16 Result table for single receiver noise level statistics

4 Discussion

After data tailoring, the transformed data was able to be imported into SoundPLAN and successfully generated the noise simulation results. However, the limitations of original data, including the lack of attributes, different classification systems for a specific object, etc. may cause the inaccuracy of simulation results. The possible solutions to improve the input data are discussed in Section 4.1. When running the noise simulation program in SoundPLAN, errors as well as warning messages may occur and pause the program, section 4.2 gives the possible solutions to these problems. Finally, the input data in this study is compared with the input data in other studies in section 4.3.

4.1 Required Improvement of the Input Data

In this section the available data in the current 3CIM model and LDVB and possible improvements are discussed, in order to provide high quality data to noise simulations conducted in accordance with the END-directive.

4.1.1 Road Dataset

Different vehicle classifications of LVDB and CNOSSOS-EU may lead to incorrect input attributes. The road dataset LVDB classifies road vehicles into two categories: heavy vehicles and light vehicles. However, CNOSSOS-EU uses a different classification. It contains five categories: 1) light motor vehicles, 2) medium heavy vehicles, 3) heavy vehicles, 4) powered two-wheelers, 5) open category that will be defined according to future needs (Kephalopoulos et al., 2012). The percentage of each vehicle type was calculated separately. The vehicle speed varies from each vehicle category and the time slices, and the speed limit, which is available in LVDB, is not actual speed. Also, the heavy vehicle percentage could be inconsistent with the CNOSSOS-EU standard due to different classification methods of vehicle types in LVDB and CNOSSOS-EU.

The traffic load was only for the weekdays, which means the noise simulation result only represented the noise levels on weekdays. Attribute *MVD_20* was the average traffic load on weekdays. The input traffic load per hour on each time slice (*veh_h_d*, *veh_h_e*, and *veh_h_e*) was calculated from *MVD_20*. Therefore, the simulation output can only represent the noise level on weekdays. If noise levels for weekends need to be taken into account, the weekend traffic load should be measured.

The road width attribute was missed in the road dataset. A moving vehicle may not be in the middle of a road, especially on the main road. This will affect the location of the noise source as well as the propagation path, and further, affect the noise levels output. 3CIM data enclosed a *TrafficArea* object class that is linked with the National Road Database (NVDB), and the road objects in *TrafficArea* were represented by polygons. However, it is hard to extract the road width from the geometry of polygons since the roads were not always regular rectangle polygons.

4.1.2 AuxiliaryTrafficArea and PlantCover object classes

Further studies are needed to reclassify the function of *AuxiliaryTrafficArea* and *PlantCover* object classes. As the ground absorption area, a ground factor that indicates the ability of acoustic absorption was required as an input attribute. The ground factor was determined by different ground classes. According to the hardness, CNOSSOS-EU divided the ground surface material into eight categories. The ground classes were coded by A-H, and each class has a ground factor. In 3CIM data, the ground class can be detected from the function attribute, which is a different classification from CNOSSOS-EU. For example, the function of *AuxiliaryTrafficArea* could be *Mjuk vägren* (soft shoulder), *Hård vägren* (hard shoulder), *Bullerskydd* (noise protection), etc. that have different hardness and acoustic absorption capacity. For the *PlantCover* object class, the function classification was in accordance with the vegetation types. For example, it could be *Gräsyta* (grass area), *Barrskog* (conifer forest), *Klätterväxter* (climbing plants), etc. The ground factors for different plant cover types need to be evaluated.

4.1.3 *CityFurniture* object class

The objects in the *CityFurniture* object class were represented as either 3D linear strings or 3D polygons. And all the objects were transformed into 2D lines. In the case study data, most of the city furniture objects were stored as 3D linear strings, while five of the geometry types were 3D polygons (Figure 4.1 left). After filtering the walls and retaining walls, there were still two objects stored as polygons. In the output shapefile, all walls and retaining walls were transformed into 2D lines (Figure 4.1 right). This might cause a problem to measure the wall thickness and the noise protection capacity during noise simulation.

If there are many polygon walls or retaining walls, a *GeometryFilter* transformer in FME could solve this problem. The transformer can split the linear string objects and the polygon objects to separate files, then two files are able to be imported into SoundPLAN as two noise protection wall Geo files.

As the noise protection wall, the reflection properties are also important in measuring the noise attenuation on the propagation path. It depends on the material of the wall, for instance, a glass or concrete wall (hard reflective) can cause 1dB reflection loss, while a highly absorbent noise protection wall can cause 8-11dB reflection loss (Murillo-Gómez et al., 2015). SoundPLAN allows users to input the reflection type of a wall (e.g. hard reflective), reflection loss on the left/right side, as well as absorption spectrum to improve the simulation accuracy.

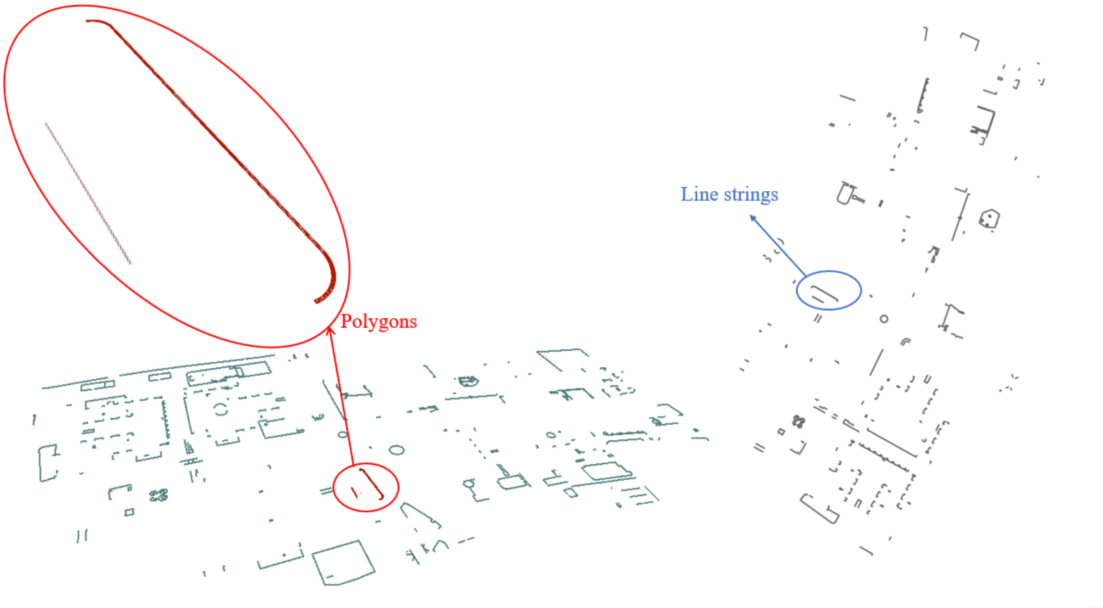


Figure 4.1 The original 3CIM CityFurniture object class (left) compare with output walls and retaining walls as 2D shapefile (right)

4.1.4 *BuildingPart* object class

Buildings are an important factor in outdoor noise propagation. The building attributes, including building height and reflection properties, were used to calculate noise attenuation. Then some of the properties were inherited by receivers in single point calculation or façade noise maps (SoundPLAN GmbH, 2019), for instance, the receivers can be generated based on the building height property.

The building height in this study was calculated from the maximum height minus the minimum height of a building part object. For the box buildings (LoD1) like the selected ones in Figure 4.2, the calculated height does represent the real building height. However, buildings could have sloping roof surfaces such as the selected ones in Figure 4.3 (left). In this case, the calculated height is the distance from the building bottom to the roof ridge. It means a building with a sloping roof was replaced by a box with the calculated height (Figure 4.3 right). Then the footprint was extracted from a box and was transformed into a 2D polygon with an attribute of the calculated height.

The transformation method may cause two problems. First, if the floor height was preset by users, the noise simulation program could generate more receivers for the roofs. For example, the building height (exclude roof) is 9m and the roof height is 3m, the user preset the floor height as 3m. For one façade of a building, there will be at least one more receiver in front of the roof, even though no resident lives in the roof part. In a large study area, it will spend more time to run the program. Second, the change in roof surface angle leads to a different acoustic diffraction path that affects the noise simulation results. Transforming the *BuildingPart* object class to CityGML format or other types of 3D data that is readable by SoundPLAN will improve the noise simulation accuracy. However, by writing the *BuildingPart* as CityGML directly in FME, the output was not able to be imported into SoundPLAN. Further studies of the *BuildingPart* data structure are needed.

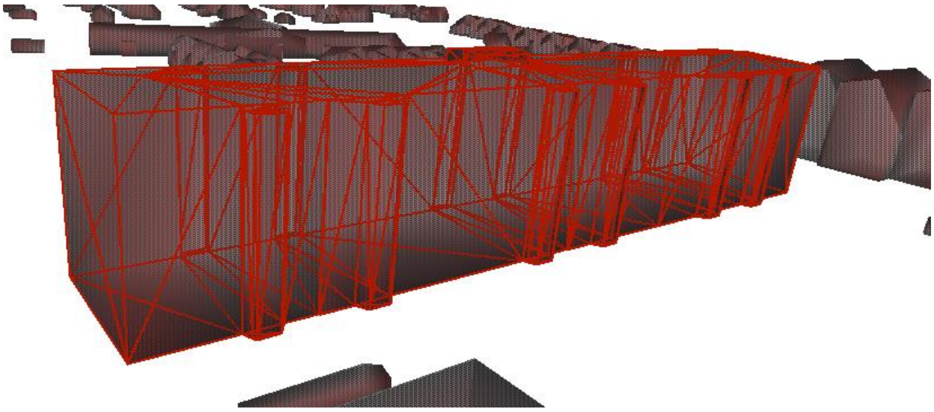


Figure 4.2 Cubic building parts in 3CIM data

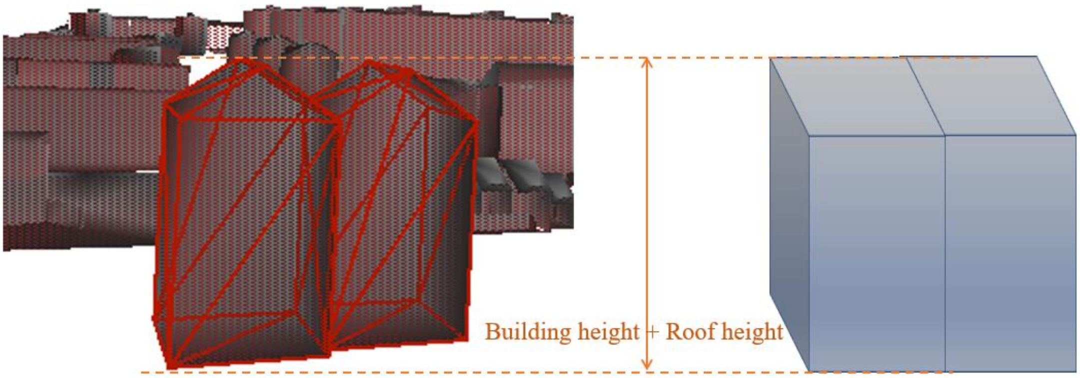


Figure 4.3 Building parts with sloping roofs in 3CIM data (left) and the replaced cubic box (right)

The material and reflective properties of windows are different from building façades. It should be taken into account in noise simulation. The *BuildingPart* used in this study was in LoD2-3, which contained boundary surfaces but not windows. Being able to locate receivers at the location of the windows could be the way of getting better exposure assessments for the people living the building. In 3CIM data the building can be represented in LoD0-4. For building parts stored in LoD3 or LoD4, the window information could be available.

Another important parameter is the building type, which is not available in the 3CIM data for now. The default building type in SoundPLAN is the main building (residential building). Users can choose to import the building type as an attribute or change it manually for specific buildings. The buildings such as dwellings, schools, hospitals, and kindergartens are considered noise-sensitive buildings in the EU directive (Kephalopoulos et al., 2012).

4.1.5 SolitaryVegetationObject object class

The solitary vegetation objects were imported as tree object type, for which a tree height attribute was required. According to the 3CIM schema, this object class contains an attribute *height* that could be used as the tree height. However, the height attribute was missed in the case study data. Thus, a self-defined value was set as the height for each type of solitary vegetation.

Another problem is the function of the solitary vegetation. This object class contains not only trees such as *Lövträd* (deciduous trees) but also *Rabatt* (flower bed), *Klätterväxt* (climbing plant), etc. The climbing plant could be with a wall or a building façade, and the height was not always measured from the ground surface as the trees. Additionally, climbing plants forms a vertical greenery system, the acoustic insulation capacity of which is different from traditional trees (Pérez et al., 2016). To improve the input data, a possible solution is reclassifying the vegetation and treating them in different ways. For instance, the climbing plant could be extracted from *SolitaryVegetationObject* and be treated as a noise protection wall with a specific noise attenuation factor.

4.2 Errors and Warnings in a Noise Simulation Process

When running the façade noise map calculation in SoundPLAN, errors or warnings may occur and sometimes cause the pause of the program. This section describes one error and three warning messages and then gives the solutions to solve these problems.

4.2.1 Road section below the ground

The digital ground model (DGM) is a continuous surface while a road object in the road database is a set of ordered line segments. Some parts of the road objects could be below the ground even though all nodes had been set above the ground. This error will pause the program and must be fixed. To solve it, users can find out the ID of a road section that causes the problem, then raise the selected node or road section by *Set objects to DGM*. By adding up the elevation, the road section will be moved to the ground surface.

4.2.2 Receiver below the ground

The bottom of a building object, as a plane, could be below the continuous surface of the digital ground model (DGM). Even though all the nodes were set above ground, some parts of the bottom plane could be below the ground model. When calculating the façade noise map, the receivers were generated from the building facades, thus some receivers could be below the ground. This generates a warning message, and the invalid receiver will be skipped, and the program will continue to calculate the noise levels for the next receiver. To solve this problem, users can select the building that the receiver was generated from and raise the building by *Set objects to DGM*. Another solution is to change the value of *Receivers in height above ground [m]* in the Calculation kernel - Run properties – Façade noise map. Although the CNOSSOS-EU recommended the receiver height is 4m, it is just a reference value and can be changed if needed (Kephalopoulos et al., 2012).

4.2.3 Receiver outside the DGM

According to the CNOSSOS-EU requirement, the receivers should generally be placed 2m in front of building façades (Kephalopoulos et al., 2012). For the buildings that are close to the boundary of the DGM, receivers generated from which could be out of the DGM boundary. This generates a warning message; the invalid receiver will be skipped and the program will continue to calculate the noise levels for the next receiver. In this study the input data was only that inside the study area. It would have been preferred to include data outside the study area corresponding to the distance of the search radius, to include all sources. Another possible solution is reducing the search radius of noise source in noise simulation setting.

4.2.4 Receiver inside buildings

A building consists of one or more building parts, which means two building façades could be very close or even touch each other. Since the receivers in this study was placed 2m in front of building façades in accordance with the CNOSSOS-EU standard (Kephalopoulos et al., 2012), some receivers could fall inside its adjacent building part. This generates a warning message; the invalid receiver will be skipped, and the program will continue to calculate the noise levels for the next receiver. Since this problem will not pause the calculation, and receivers inside building block account for a small proportion of the total receivers (98/10919), these receivers can be taken out. Pamanikabud & Tansatcha (2003) provided a solution that removed receivers inside buildings and added new receiver points instead. The new receiver points were on the corner of the barrier, as well as the center of each side of the barrier (Figure 4.4).

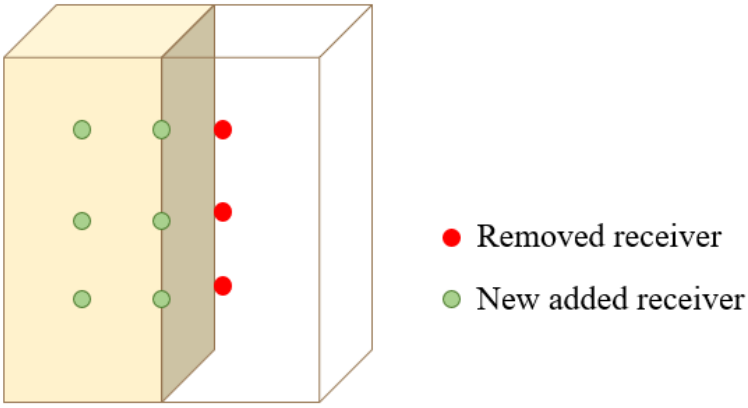


Figure 4.4 The replacement of receivers inside buildings.

4.3 Comparsion of the Input Building and Road Data in Other Studies

3D city models have been used in noise simulation studies in many countries. To improve the simulation result, building was imported as 3D geometries. For example, Kavisha et al. (2017) used CityGML data with an updated noise ADE to evaluate the city noise level in Netherlands. The CityGML data includes buildings was tailored by a 3D modelling software, which lift the 2D polygons to required height. It means the input buildings were LoD1 blocks without roofs. Similarly, the 3D building constructed by Stoter et al. (2020) was also from 2D data and was transformed into LoD1 building blocks without roof structures. The problem also exists in this study.

Although the data source of buildings was in 3D, in the noise simulation process it only used the 2D boundaries and the value of building height. More building details like slope roofs, windows that significantly affect the noise levels were not considered.

Another study from Kurakula et al. (2007) included the roofs information but did not use CityGML data. The buildings were stored as 3D shapefile with roof geometries (Figure 4.5). It used a different noise simulation software, and the receivers (observation points) were not generated form the buildings, however, the roof effect was considered. This could be a solution to add roof information.

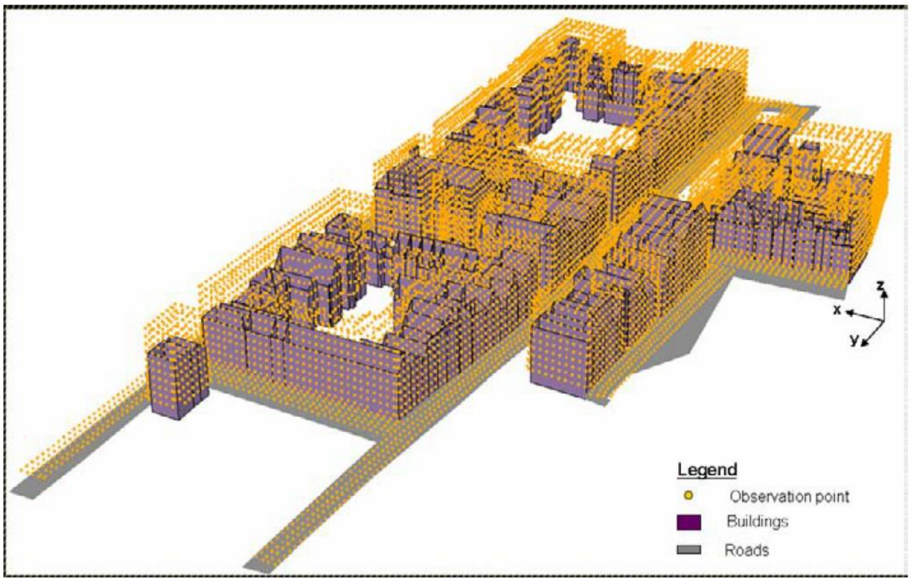


Figure 4.5 Buildings in 3D shapefile with roofs information (Kurakula et al., 2007)

In many of the noise simulation use cases (Kavisha et al., 2017; Czerwinski et al., 2007; Stoter et al., 2020) the roads were imported as 3D multi-surface. In this study, the shapefile lines only represent the central line of the roads. By using roads that were represented by multi-surface the noise simulation program can detect the road width and improve the accuracy of noise source location. The road attributes such as traffic load and speed limit were stored in the noise ADE.

5. Conclusions

To perform road traffic noise simulations in the study area, a simulation software was needed. The software should meet two requirements: First, the CNOSSOS-EU standard must be supported to make sure that Sweden can complete the tasks from the END project. Second, the software is accessible during the master thesis project. SoundPLAN met these requirements and was therefore selected.

The main task of this study was to transform the 3CIM data to function as input data to the road traffic noise simulations. Due to the height information (DGM) was not contained in the 3CIM data and the traffic data in 3CIM encloses few traffic attributes, these data had to be obtained from other sources. The first supplementary data source was a Digital Elevation Model (DEM) in Geotiff format. DEM was transformed and imported into SoundPLAN to provide the terrain information. The second supplementary data source was the municipality road dataset from the local road database (LVDB). It contains more traffic attributes, especially the traffic intensity, that were important into the noise simulation.

All the original data, including 3CIM, DEM, and road dataset were tailored by the ETL tool FME. Noise attributes (e.g. traffic load, speed limit) were generated based on the original data, CNOSSOS-EU model as well as the SoundPLAN requirements. Data transformation included attributes calculation, attributes reclassification, building footprint extracting, etc. The FME script (Link for the FME scripts) is open source and allowed to be used to benefit further studies. After running the script, the input data will be generated in the target folder. The DEM data should be imported as elevation points, then by executing the data a DGM Geo file will be created by SoundPLAN. Other input data should be imported as specific object types (e.g. Road, Tree), after mapping the attribute between input data and SoundPLAN required parameters, a Geo file will be created for each input file.

For improving the simulation accuracy, the road dataset needs to reclassify the vehicle type to be consistent with the CNOSSOS-EU standard. Also, the road width should be included as an attribute in the road dataset from LVDB, or the road surfaces in the *TrafficArea* object class of 3CIM could be used to replace the LVDB data. Further studies are necessary to reclassify the function of *AuxiliaryTrafficArea*, *PlantCover*, and *SolitaryVegetationObject*, in order to decide the noise attenuation factors for objects in different categories. For the *SolitaryVegetationObject*, tree height information needs to be filled in the *height* attribute. It will be better to separate the 3D linear strings and 3D polygons in the *CityFurniture* object class then define the wall thickness in different ways. Or they could be stored in different object classes. To consider the effect of different roof types and windows in *BuildingPart*, they should also be imported into noise simulation software. However, the problem for importing CityGML roofs and windows has not been solved.

Reference

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Appendices

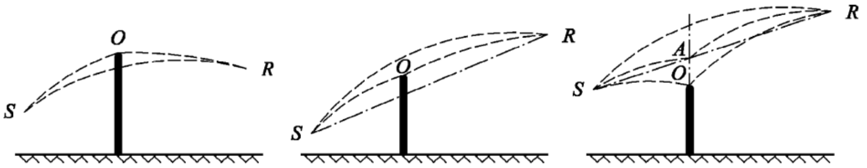
Appendix I: Sound Diffraction

Diffraction is when the sound wave encounters an obstacle or opening, interference or bending will occur around the corners of an obstacle or through an aperture into the region of the geometrical shadow of the obstacle/aperture.

SoundPLAN gives the diffraction path in favorable (Figure I-a) and homogenous conditions (Figure I-b), where *S* is the source of noise, *R* is the receiver, and *O* is the diffraction point.

Favorable condition

In the 3rd case, *A* refers to the intersection of the straight sound ray *SR* and the extension of the diffracting obstacle.



1st case 2nd case 3rd case

Figure I-a Sound diffraction path in favorable condition (Kephalopoulos et al. 2012)

Homogenous condition

The *δ* refers to the path difference between the diffracted path and the direct path. O_1 and O_2 are diffraction points.

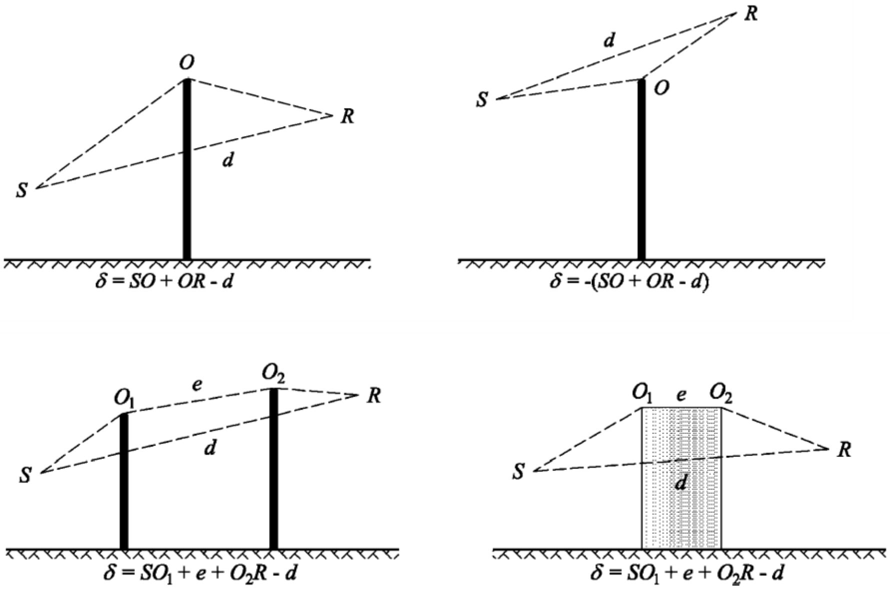


Figure I-b Sound diffraction path in homogenous condition (Kephalopoulos et al. 2012)

Appendix II: 3CIM Code List (3CIM_ver2)

Table II.1 Code list of Auxiliary Traffic surface material

Code	Description
10000	Asphalt
10001	Concrete
10002	Paved
10003	Cobblestone
10004	Gravel
10005	Track on the way
10006	Track with substructure
10007	Earth
10008	Sand
10009	Grass
10010	Wood
10011	Steel
10012	Marble
10013	Unknown