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3D geospatial data requirements for simulating noise using the Nord2000 model:

Case study of the impact of building façade types and roof configurations on simulated traffic noise levels

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Abstract

The increasing global population and urbanization have led to a significant problem of noise pollution in many urban areas. With 85% of the European population living in urban areas, understanding noise pollution in the context of urban densification is crucial. The primary sources of noise pollution in cities are traffic, aircraft, railways, and industries, with tall buildings and narrow streets, exacerbating the issue. Exposure to noise pollution can cause both short-term and long-term health problems, such as headaches, anxiety, sleep disturbances, hearing loss, high blood pressure, and heart disease. Effective urban planning can mitigate noise pollution by incorporating noise reduction measures, such as sound barriers, vegetation, and building design. Monitoring and evaluating noise levels is critical for decision-makers and urban planners to create safer and healthier cities. Using a 3D city model, noise simulation is used to assess noise levels in outdoor environments. Geographic Information Systems (GIS) play a crucial role in mapping noise, allowing for the integration of various data sources, such as noise measurements, land use patterns, and demographic information, to identify areas with high noise exposure that may require mitigation measures.

This report describes a study that investigates the effects of changes in input data on noise simulation output in urban areas using 3D city models as input. The study focuses on pre-processing and adapting the 3D city model data according to the requirement of a noise propagation model (Nord2000) considering barrier objects such as plant cover, vegetation, buildings, and roads as sources of noise. The research questions addressed in this study include input geospatial data requirements for the Nord2000 model, the effects of changes in acoustic properties for different building façade types on simulated noise values, and the effect of roofs on noise levels. The study provides some recommendations of how 3D city models should be designed for supporting noise modelling.

Keywords: *noise simulation, traffic, Nord2000 model, building façade types, roof configurations, geospatial data, 3CIM, SoundPLAN, barrier objects, acoustic properties, urban areas.*

Contents

1 Introduction

1.1 Background

Given the joined effect of a growing global population and urbanization, noise pollution has become a serious problem in many urban areas. According to recent United Nations (UN) forecasts (UN, 2022), there will be 9.7 billion people by 2050, with 68% of them living in urban areas. As stated by the European Commission, 85% of the European population currently resides in urban areas (Ritchie & Roser, 2018). Therefore, understanding noise pollution in the context of urban densification is interesting. There are several factors that contribute to noise pollution in cities. One is the number of people and vehicles. With so many people living and moving around in proximity, there is bound to be a lot of noise (i.e., noise resulting from traffic, aircraft, railways, and industries). Also, tall buildings and narrow streets related to the urban environment can create a sort of echo chamber, amplifying the sound of traffic and other noises (Can et al., 2015; Cowan, 1993; Picaut et al., 2005). It is important to be aware of the potential risks of exposure to noise and to take steps to protect people from its harmful consequences.

The effects of noise pollution are wide-ranging and potentially very harmful. Short-term exposure to loud noise can cause symptoms like headaches, anxiety, and sleep disturbances (Afarinesh et al., 2018; Pandey et al., 2015). Long-term exposure can lead to more serious problems like hearing loss, high blood pressure, and heart disease (Beutel et al., 2020; Dzhambov & Lercher, 2019; Stansfeld & Matheson, 2003). In the EU, more than 120 million people, almost 30% of the population, are estimated to be exposed to road traffic noise levels above the residential target value of 55 dB(A) ($L_{den} \geq 55$ dB) (WHO, 2004). It is therefore vital to comprehend how the generated noise as a source affects humans as receivers. Noise levels need to be measured regularly and communicated to policymakers, experts, and the public to plan essential noise-reduction measures (Kurakula & Kuffer, 2008; Lu et al., 2017; Pamanikabud & Tansatcha, 2009). In Sweden, exposure to noise pollution is regulated by law and controlled in the early stages (e.g., detailed development plan) of urban planning (Boverket, 2020).

Urban planning plays a crucial role in controlling noise pollution in urban areas. Effective planning can help to minimize the impact of noise on residents by considering various factors that influence transport noise, such as traffic volume, vehicle type, and traffic conditions (Purkis, 1964). Also, some other sources of noise (e.g., railways and aircraft), can be discussed and investigated, in urban planning. A range of noise reduction measures, including sound barriers, vegetation, and effective building design, can be incorporated into urban planning to mitigate noise pollution. By predicting and evaluating the propagation of sound waves and understanding how they interact with the urban environment, the effective design of urban furniture can help to reduce noise levels in urban areas (Morillas et al., 2018). Afterwards, noise can be reduced in a targeted way by taking into account sound barrier objects[1] or vegetation in urban planning (Law et al., 2011; Ranjbar et al., 2012). Noise simulation is used for assessing noise levels in outdoor, industrial, and even indoor environments in urban management. In this study, outdoor noise levels were assessed considering receivers or

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[1] "Barrier objects" refer to physical objects such as walls, fences, or hedges that act as a barrier to the propagation of sound waves. These objects can help to reduce noise pollution in urban areas by blocking or absorbing sound waves.

observers located in a building with open windows (considering residents are directly exposed to outdoor noise).

The evaluation and monitoring of noise levels has become a critical concern for decision-makers and urban planners to make cities safer and healthier places for their citizens. The WHO (World Health Organization) Constitution came into force on April 7, 1948, and since 1980 (Berglund et al., 1999), the WHO has issued guidelines for the protection of human health, particularly against public noise and night noise (WHO, 2005, 2009, 2018). At the European Union scale, the Environmental Noise Directive (END) 2002/49/EC provides an approach related to assessing and managing environmental noise and harmful effects. According to the directive, ‘noise mapping’ should present an existing or predicted noise situation in terms of a noise indicator, the number of people affected in a certain area, or the number of dwellings exposed to certain values of a noise indicator in a certain area (Directive, 2002). The directive states that all EU member states must prepare a strategic noise map to inform the public about noise pollution and its effects. Geographic Information Systems (GIS) play a crucial role in mapping noise, as highlighted by de Kluijver and Stoter (2003) because they allow for the integration of various data sources, such as noise measurements, land use patterns, and demographic information. For example, GIS can be used to overlay noise levels with population density maps to identify areas with high noise exposure that may require mitigation measures. In this regard, to visualize strategic noise maps, a 3D simulation model of noise pollutants is commonly used (Biljecki et al., 2015; Hadzi-Nikolova et al., 2012; Silva & Mendes, 2012; Yao et al., 2006). Manvell and van Banda (2011) investigated what indicators influence the output quality of the noise mapping process to establish good practice guidelines based on a report from the European Commission (2006). Additionally, the END authorized the European Commission to establish a common framework for noise assessment methods.

There are many noise simulation models used by various countries and their differences are mainly related to source-based noise and characteristics of noise propagation (Ibili et al., 2022; Khan et al., 2021; Wolniewicz & Zagubień, 2015) . Legislation, road maintenance, traffic management, low-noise tyres, low-noise vehicles, and driver behaviour are some source-based elements that influence the adoption of different simulation models across countries. In fact, the importance of these factors varies by country, for example, a country that performs road renovation every 5 years is different from a country that does it every 10 years. Likewise, in one country, drivers are accustomed to honking, which can be a different source, but in another country, drivers use the horn less (driver behaviour). The task of harmonized data model that could be applied throughout the European continent was assigned to the European Commission (CORDIS, 2001; Kumar et al., 2020). In this regard, the Common NOise aSSessment methOdS in EUrope (CNOSSOS-EU) was introduced as a harmonized model for noise assessment, which is a critical tool for measuring and managing noise pollution in the European Union (Kephalopoulos et al., 2012).

The European Commission has developed CNOSSOS-EU to be utilised in noise simulations based on road traffic, rail traffic, aircraft noise, and industrial noise. It is intended to be used after adoption by Member States for strategic noise mapping as required by the END (Kephalopoulos et al., 2012; Kephalopoulos et al., 2014). According to END, until these common assessment methods are implemented, EU Member States may utilize one of their national assessment methods as stated in paragraph 2.1 of Annex II of the END (Directive, 2002). Meller et al. (2022) have prepared a table outlining in which countries noise traffic models are developed. In Nordic countries (Denmark, Norway, Sweden, Finland, and Iceland), there are two models: Nord2000 (Nordic noise prediction method) (Jonasson & Storeheier, 2001; Kragh, 2000; Kragh, 2011b) and RTN96 (Nordic prediction method for Road Traffic Noise) (Bendtsen, 1999).

Nord2000 considers parameters in more detail than CNOSSOS-EU. So, the disparity in results could be related to differences in CNOSSOS-EU and Nord2000 parameterizations (e.g., handling of diffraction and refraction) (Khan et al., 2021). Nord2000 models can be used for noise prediction in more complex situations. Nord2000 uses 1/3 octave bands, advanced outdoor propagation models, and more vehicle and ground categories (Larsson, 2016).

There are several tools that perform noise simulations e.g., SoundPLAN (SoundPLAN, 2020), CadnaA (DataKustik), Predictor-Lima (SoftNoise) and NoiseModelling (Noise-planet), etc. SoundPLAN is used in this study to execute noise simulations based on the Nord2000 model. This software allows for the 3D simulation of noise using a 3D city model as input data.

The use of 3D city models has become increasingly prevalent in urban planning and environmental assessment (Czerwinski et al. (2006a); Kurakula et al. (2007); Lu et al. (2017); Manvell and van Banda (2011)). A 3D city model is a digital model of urban areas representing buildings, land surfaces, vegetation, city furniture, infrastructure, and transportation on a three-dimensional scale. The information and parameters that can be incorporated into a 3D model may vary based on the user's needs and preferences. It is worth noting that 3D models can be developed using various frameworks or standards. For instance, the 3D city model used in this study for noise simulation is based on the 3CIM (3D City Information Model), which is currently being developed in Sweden (Harrie et al., 2021; Uggla et al., 2023). 3CIM is a national standard developed by representatives from the urban planning offices at the municipalities of Stockholm, Gothenburg, and Malmö, along with Lund University. The model is based on CityGML (City Geography Markup Language), and the model is currently under implementation in the three cities.

When conducting noise simulations, it is important to consider both input data characteristics and configuration parameters, as they can have a significant impact on the results obtained. To determine the sensitivity of a noise simulation to a particular set of parameters, it is crucial to identify and prioritize the various components involved (Aumond et al., 2021). For instance, road traffic factors, including car categories, vehicle speeds (either speed limit or actual speed), and the number of vehicles, can affect the simulation results. Similarly, the sound propagation model, which considers factors such as temperature, humidity, and wind conditions, can also impact the results. Additionally, geometrical configuration parameters, such as the location of buildings and the façade noise absorption coefficients or reflection coefficient, as well as the level of detail (LOD) in the 3D city model, are essential considerations. Lastly, configurational parameters, such as the number of reflections and the acoustic properties of different façade materials, must also be considered to ensure accurate and reliable noise simulation results. In addition to the mentioned factors, there may be other variables that can significantly impact the results. Ultimately, having a comprehensive understanding of the inputs and settings of noise simulation software is crucial for accurate and effective noise mapping and management in urban environments.

1.2 Problem Statement

Preparing input data for noise simulation can be challenging as the data often originates from various sources, such as 3D city models, road databases, meteorological databases, etc., that are not optimized for noise simulation. This raises two main questions: (1) how to tailor the input data from these different sources for use in noise simulation, e.g., for the Nord2000 model, and (2) how sensitive the results of the noise simulation to the quality of the input data are. Important quality aspects in the input data are, for example, representation of buildings (level of detail), the building façade surface material (e.g., acoustic properties), and the roof configuration.

1.3 Aims

The aim of this study is to investigate the effects of changes in input data on noise simulation output in urban areas using 3D city models (3CIM) geodata as input. The study focuses on pre-processing and adapting the 3CIM model according to Nord2000 requirements as implemented in SoundPLAN. The study considers barrier objects such as plant cover, vegetation (e.g., trees), buildings as receivers, and roads as sources of noise. Specifically, two simulation scenarios are compared to investigate the impact of densification, one scenario assuming both current and planned buildings and the other scenario assuming only current buildings. In each scenario, the effect of noise reflection on three types (very hard, hard, soft) of assumed building façades is examined. Additionally, the effect of roofs on noise levels is investigated.

In summary, the following research questions are addressed in this study:

- What is the input geospatial data requirements for the Nord2000 model?
- How do changes in acoustic properties (e.g., reflection loss, reflection coefficient) for different building façade types affect simulated noise values in the Nord2000 model? How sensitive are these effects?
- How does the roof affect the value of simulated noise level in Nord2000 model?

1.4 Limitations

There are several limitations to this study that should be acknowledged. Firstly, we do not have observed noise values to compare with our simulated results, which makes it challenging to verify the accuracy of our noise prediction models. Secondly, the Nord2000 model, which is used to simulate noise propagation, requires more detailed input data compared to other models, resulting in higher demands on computer resources and computation time. As a consequence, the applicability of Nord2000 is limited to smaller geographical areas, and its use may not be feasible for large-scale studies. Lastly, this study only uses one 3D city model (3CIM), one noise propagation model (Nord2000), and one software (SoundPLAN). While these models and software have been validated in previous studies, it is possible that other models and software may have yielded different results. It should be noted that 3CIM is a relatively recent development, and the application of 3CIM in research is not widespread yet.

1.5 Disposition

Chapter 2 presents the theoretical framework of noise simulation models. It covers the fundamental principles of noise simulation, including the physics of sound propagation and the measurement of noise. The chapter also reviews the existing noise simulation models and their limitations. In chapter 3, the role of 3D city models as input data for noise simulations is examined. The chapter explains the advantages of using 3D city models, such as the ability to model complex urban structures, and the challenges associated with their integration into noise simulation models. The chapter also highlights the importance of accurate and comprehensive 3D geodata for noise simulations. Chapter 4 describes the approach used to identify the 3D geodata input requirements for noise simulations. The selection criteria for the case studies and the methods used to collect and process the 3D geodata are also presented in chapter 4. The chapter also outlines the noise simulation models used and the parameters selected for the simulations.

The results of the study are presented in chapter 5. The section provides a comparative analysis of the noise simulation results based on the different scenarios. The discussion, chapter 6, interprets the results and provides insights into the implications of the findings. It discusses the strengths and weaknesses of the noise simulation models and the 3D geodata used. The section also highlights the importance of considering the uncertainties and limitations associated with the noise simulation models and the input data. The conclusions in chapter 7 summarizes the main findings of the thesis and provides recommendations for future research. It emphasizes the importance of using accurate and comprehensive 3D geodata as input for noise simulations and the need for improved noise simulation models. The conclusion also highlights the potential applications of the findings in urban planning and policymaking.

2 Theoretical Framework of Noise Simulation Models

This chapter provides an overview of the theoretical framework behind noise simulation models. Section 2.1 covers sound theory in the urban environment. This includes a discussion of sound pressure level (section 2.1.1), which is a measure of the sound energy present in a given area. The concept of octave band is also introduced (section 2.1.2), which divides sound into frequency bands. Section 2.1.3 explores the decibel scale, which is used to express sound intensity relative to a standard reference level. A-weighting, which is a commonly used weighting scale that accounts for how the human ear perceives sound, is discussed in section 2.1.4. Moving on to section 2.2, the chapter discusses noise simulation, including various noise indicators in road traffic, such as equivalent noise level (2.2.1). The importance of input data parameter settings is described, in section 2.2.2, including factors such as the location of the sound source, the distance to the receiver, and the environmental conditions.

Section 2.3 focuses on the CNOSSOS-EU model, which is a European Union directive for the assessment of environmental noise. The model is described in detail, including its input data requirements and its use in various applications. Section 2.4 delves into the Nord2000 model, which is a noise simulation model developed in Scandinavia. The chapter discusses the model's propagation model and its input data specifications, including meteorological data, terrain data, and emission source data. In section 2.5, the chapter compares the CNOSSOS-EU and Nord2000 models, highlighting their differences and similarities. This includes a discussion of their input data requirements, modelling approaches, and output parameters. Finally, section 2.6 focuses on noise modelling tools, including the SoundPLAN software. The chapter provides an overview of the software's capabilities, including its ability to simulate noise propagation and to calculate various noise indicators. Section 2.7 refers to the sensitivity of different building façade materials on noise absorption and reflection.

2.1 Sound theory in the urban environment

Early study of noise propagation in an urban environment were made by Wiener et al. (1965). Wiener used acoustic and meteorological field tests to study sound propagation on urban streets. The mathematical studies of urban sound propagation are challenging due to the complexity of the area. Various constructional interference affecting noise propagation, such as buildings, plants, cars, people, and urban furniture affect noise propagation and create a complicated sound field. To address this complexity and obtain an analytical or numerical description, 2D and 3D computer simulation of noise can be an effective technique for determining noise dispersion.

Several noise simulations models have been proposed such as: NMPBRoutes-96 (Di Martino et al., 2013), CoRTN (DoT, 1988), FHWA (Barry & Reagan, 1978; Seong et al., 2011), RLS 90 (für Verkehr, 1990), British Standard (BS), ISO 9613 and Nord2000 (Jonasson & Storeheier, 2001; Kragh, 2011b), CNOSSOS-EU (Kephalopoulos et al., 2012). The following section includes a brief review of the mathematical theory of CNOSSOS-EU as the standard model provided by European Commission and the Nord2000 as the model applied in this study. Before going over these models, the fundamental concept of sound propagation and the indicators used to measure the noise level are discussed.

2.1.1 Sound pressure level

When the wave front is emitted from the source, it expands by compressing the air molecules, Figure 2.1a. How far this wavefront can advance in an outdoor environment depends on several factors, for example (Figure 2.1b): geometric divergence (depends on the source, the distance, and the propagation field), atmospheric absorption (depends on frequency, humidity, and temperature), topography (existing noise barriers, hills, buildings etc. which create reflections, diffractions and shadow zones), ground impedance (depends on the characteristics of the ground and the angle of incidence of the waves), temperature (increases and decreases with height), wind (wind direction) and turbulence (depends on distance, frequency and amplitude of the local variations like temperature, wind velocity, etc. create fluctuations of sound waves which induce scattering of the sound energy) (Embleton, 1996; Ingård, 1953; Piercy et al., 1977; Plovsing, 2007). Considering road traffic as the noise source and building occupants as the receivers, it is important to estimate how much noise reaches these receivers according to END.

Total noise attenuation is the sum of all forms of attenuation that may be occurred in the sound path from source to receiver and is determined as Equation 2.1 (Murphy & King, 2022):

$$A_{tot} = A_{div} + A_{atm} + A_{topography} + A_{ground} + A_{other} \quad [dB] \tag{2.1}$$

The sound power, L_p, represents the level of noise coming from any noise sources after all mentioned attenuation (Equation 2.2).

$$L_p = L_W - A_{tot} \quad [dB(A)] \tag{2.2}$$

The sound pressure level at the receiver, L_p, and L_w, is the sound power at the source.

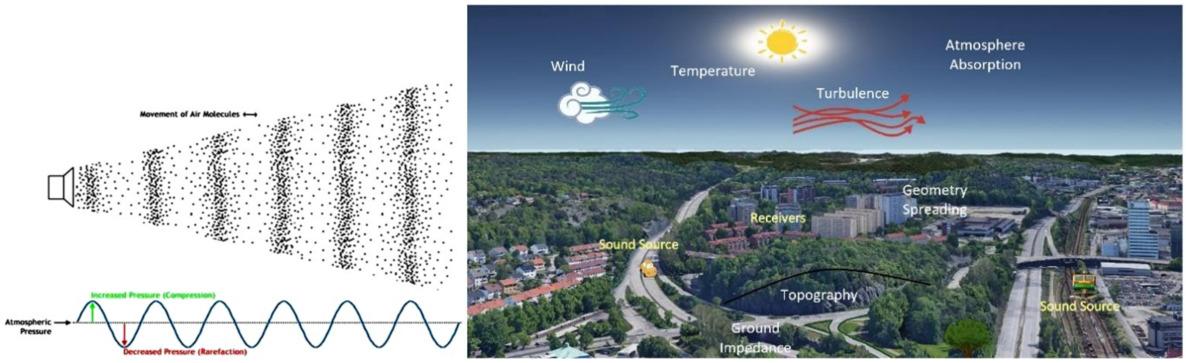

Figure 2.1 - (a) sound propagation through air (Coules, 2018) (b) Propagation of Sound in urban area (Google earth, Gothenburg)

2.1.2 Octave Band

All sounds have three basic properties: frequency, amplitude, and wavelength. Noise is generally made up of a range of different frequencies. The average healthy human ear can detect sounds from about 20 to 20,000 Hz. The produced range of frequency of road traffic is 50 to 7000 Hz (Murphy & King, 2022). Therefore, the entire frequency range is usually divided into set of frequency intervals called bands (e.g., octave bands) to make the information more manageable. This implies that this kind of frequency division, which is connected to how the human ear perceives sound, provides the possibility to compress the amount of information.

Octave bands are employed to make simple to analyse the frequency information in a sound. Different frequencies are grouped together in octave bands. According to Table I.1 in Appendix I (See: Murphy and King (2022)), each band covers a particular range of frequencies (Crocker, 1998). The upper and lower frequency of an octave band is calculated according to Equation 2.3:

$$f_L = \frac{f_c}{\sqrt{2}}, \text{ and } f_U = \sqrt{2} f_c \tag{2.3}$$

f_c is identified as the centre frequency. This kind of division is used in CNOSSSOS-EU model.

The one-third (1/3) octave band approach is similar to the octave band (1/1) analysis, but third octaves are used instead. In this type of division, three bands per octave are computed instead of one, Equation 2.3. This approach allows to compute the sound pressure level caused by a point source, in more detail. Table I.2 in Appendix I defines the frequency range for each one-third octave band, while mathematically the relationship between centre, upper and lower frequencies may be calculated as Equation 2.4 (Crocker, 1998):

$$f_L = \frac{f_c}{2^{\frac{1}{6}}}, \text{ and } f_U = 2^{\frac{1}{6}} f_c \tag{2.4}$$

The one-third octave band is used in Nord2000.

2.1.3 Decibel scale

Sound is usually measured using the decibel (dB) scale. In simple terms, the decibel is a ratio of one pressure to another. It uses a logarithmic scale. For ambient noise, the sound pressure level, L_p, in decibels is calculated as Equation 2.5:

$$L_p = 10\, log_{10} \left(\frac{p}{p_0}\right)^2 \quad [dB] \tag{2.5}$$

p is the sound pressure being measured and p_0 is the reference sound pressure (SPL), 2×10^{-5} N/m^2 (or 20 µPa). The reference sound pressure corresponds to the human hearing threshold. The lowest sound pressure a healthy human ear can perceive is 1000 Hz (Murphy & King, 2022). As a result, a decibel is a logarithm of a ratio of one sound to the lowest sound that a healthy human ear can hear (table in Appendix II, see: Talbot-Smith (2012)).

2.1.4 A-weighting

The human ear does not react to sounds with different frequencies in the same way. Humans frequently perceive lower-frequency sounds as being less intense. In 1933, Fletcher and Munson investigated how people reacted to sounds played at different frequencies at the same intensity (Fletcher & Munson, 1933). This work led to the development of A-weighting, which is frequently used in ambient noise research. According to Fletcher and Munson work, the human ear does not perceive a sound produced at 100 Hz and 60 dB as having the same strength as a signal played at 1000 Hz and 60 dB. In order to take this into account, the A-weighting method is used in environmental noise studies in an effort to replicate the function of the human ear. It is generally measured in dB(A) units. For comparison, the dB scale is based on sound intensity only, while the dB(A) scale is based on both sound intensity and the response of the human ear. Therefore, dB(A) helps determine when noise can harm hearing (Charbonneau et al., 2012; Murphy & King, 2022).

2.2 Noise simulation

2.2.1Noise indicators in road traffic

To calculate traffic noise, the concept of continuous noise is mainly used, that is, noises that are relatively constant over time, T, may be classified as continuous noise. Since the cars are in traffic during the day and night, they can be considered as a source for this type of sound and used to calculate the noise simulation. This is called the Continuous Equivalent Noise Level, L_{eq}. This metric is an energy-based indicator because it represents the total amount of sound energy over a specified period. It is a constant and continuous sound level of the same sound energy as the oscillating noise measured in the same time interval, Equation 2.6 (Berger, 2003).

$$L_{eq,T} = 10\,log_{10}\frac{1}{T}\int_0^T \left(\frac{p(t)}{p_0}\right)^2 dt \quad [dB] \tag{2.6}$$

T is the time period over which measurements occur, $p(t)$ is the instantaneous acoustic pressure and p_0 is the reference sound pressure level (20 µPa).

$L_{Aeq,T}$ or just L_{Aeq}, is the energy equivalent A-weighted sound pressure level during the period T. This is the constant sound level which during the period T produces the same sound energy as the varying sound levels from the traffic (Larsen, 2007). The L_{Aeq} indicator is the basis for L_{den} indicator. L_{den} is a day, evening, and night noise indicator (Kragh et al., 2006).

L_{den} and L_{night} are two universal noise indicators defined by the EU Directive 2002/49/EC (According to END Article 6) to be used in the development of strategic noise maps across the EU. L_{den} is determined by Equation 2.7 (Kragh et al., 2006):

$$L_{den} = 10\,log_{10}\left(\frac{1}{24}\right)\left(T_d.\,10^{\frac{L_{day}}{10}} + T_e.\,10^{\frac{L_{evening}+5}{10}} + T_n.\,10^{\frac{L_{night}+10}{10}}\right) \quad [dB(A)] \tag{2.7}$$

L_{day} represents the A-weighted long-term average day-time noise level (between the hours of 06:00 and 18:00 measured) over 1 year, T_d = 12, $L_{evening}$ represents the A-weighted long-term average evening-time noise level (between the hours of 18:00 and 22:00) measured over 1 year, T_e = 4, and L_{night} represents the A-weighted long-term average night-time noise level (between the hours of 22:00 and 06:00) measured over 1 year, T_n = 8. The definitions of day, evening, and night vary throughout the Nordic countries (Table 2.1).

Table 2.1 - Definitions of day, evening and night for use when calculating L_{den} in the Nordic countries (Kragh et al., 2006).

	Denmark (DK)	Finland (FI)	Norway (NO)	Sweden (SE)
Day	07-19	07-19	07-19	06-18
Evening	19-22	19-22	19-23	18-22
Night	22-07	22-07	23-07	22-06

Additional weighting factors (+5 for $L_{evening}$, +10 for L_{night}) are included to consider that noise is generally more irritating and problematic for public health in the evening and at night. Because of this additional weight, L_{den} will almost always exceed the eigenvalues L_{day}, $L_{evening}$, and L_{night} (Murphy & King, 2022).

According to END Article 7(1), environmental noise pollution should be assessed using strategic noise maps of roads, railways, airports, and agglomerations using developed noise indices L_{den} and L_{night}. L_{den} is an annual noise indicator representing the average day-evening-night- time A-weighted equivalent sound pressure level over a complete year. In this study, according to Equation 2.7, L_{den}'s strategic noise map for road that is used as a source in a defined study area has been surveyed.

2.2.2 Input data

To acquire an accurate simulation of a noise map, three types of data are required: noise sources, interface medium, and receivers. Firstly, noise source information can include road, rail, industry, aircraft, etc. For example, in the case of road traffic noise, type of vehicles light or heavy and number of cars passing routes are needed. The level of noise produced by a vehicle is highly dependent on its travel speed, which affects the contribution of each source mechanism. At low speeds, the sound of the engine dominates, while the sound of the tires and the road becomes more prevalent at higher speeds. The speed at which rolling noise begins to dominate engine noise is called crossover speed. It depends on the car model. Heavy vehicles have higher crossover speeds than light vehicles, and electric vehicles (with minimal engine noise) have lower crossover speeds (Beckenbauer, 2013; Murphy & King, 2022).

Table 2.2 - An overview of the input data required for noise mapping (Kurra & Dal, 2012).

Data	Parameters				Acoustical data
Source & emission	**Road traffic**	**Railway traffic**	**Aircraft traffic**	**industry**	
	• Road geometry • Gradient • Curvatures • Surface cover • Speed • Volume of traffic • Heavy vehicle percentage • Type of traffic flow • Traffic lights	• Number and types of trains • Average speed Sirens • Railway structure (in cuttings, level or elevated) • Type of rails, ballasts& ties • Bridge structures	• Airport plan • Runway configuration • Flight operations (daily, yearly etc.) • Types of aircrafts	• Layout plan for open air activities • Factory buildings • Manufacturing process • Indoor -outdoor equipment • Operation modes (hourly, daily, weekly)	– Sound power levels in L_w, dBA and the spectral values – Source directivity – Reference sound pressure levels with temporal and spectral variations For complex sources: – Contributions from individual parts
Physical environment	**Ground cover and woodland**	**Buildings**	**Obstacles**	**Meteorological factors**	
	• Type of surface (sound absorption coefficient) • Width of surface under sound path • Surface area Configuration of different surface types • Type of plants • Configuration of trees (deciduous, evergreen, etc)	• Location • Geometry • Façade shape (balconies etc.) • Number of floors (or total height) • Function • Façade cover (sound reflection properties)	• Natural (topography) or built barriers • Location (distance from source) • Thickness • Length • Height • Surface type • Top profile of screens • Surface cover • Constructional material	• Wind gradient • Temperature gradient • Humidity (air absorption) (Short-, mid- and long-term average values) • Favourable conditions increasing noise levels	– Effects of physical factors on immission values caused by wave divergence absorption, diffraction, refraction, scattering of sound – Total sound attenuation
Demographic	**Land use information and applicable noise limits**	**Population structure**	**Building and usage**	**Future plans about area**	
	• Urban residential • Suburban& rural • Healthcare buildings • Educational buildings • Administrative area • Shopping centres • Industrial and mixed zones • Touristic area (hotels, motels) • Recreational and entertainment area • Parks& cemeteries	• Total population • Number of residents for each building • Social, educational, and economical characteristics of community • Seasonal activities (in touristic areas)	• Sensitivity to noise • Indoor noise limits • Times of occupation (Daily, yearly) • Open/closed windows • Existence of AC equipment • Indoor noise sources (background noises) • Layout of rooms Building construction	• On-going and future constructions • Extension or modification of noise sources • Existing noise action plans	– Noise -dose and response relationships for various types of land uses – Noise levels and performance effects Outputs from noise maps: – Number of people and buildings exposed to various noise levels – Number of buildings having quiet façades

Secondly, in order to carry out accurate noise simulations, it is essential to have data related to the interface medium that has the potential to reduce noise levels. Urban design factors such as ground cover, trees, foliage, walls, barriers, and the topology of the area play a crucial role in noise attenuation, as they were mentioned in Section 2.1.1.

Finally, the last required input dataset is related to the total number and placement of the noise receivers. Given that receivers are assumed to be individuals, adding receivers at specified locations on building façades in software is required. These locations can be dependent on building height, height of floors and the distance between receivers within a floor. In general, geometrical information of building impacts the path of sound waves. A list of input data for noise mapping calculation is presented by Kurra and Dal (2012), see Table 2.2.

Noise simulation software considers these three types of data. The source, propagation medium, and input data characteristics are where they differ from each other the most, e.g., NMPB2008 which is updated version of NMPB96 (France), CRTN (United Kingdom), FHWA introduces Traffic Noise Model (TNM) (United States), CNOSSOS-EU (The Proposed Common European Method), RLS 90, and Nord2000 (Nordic countries).

To give the reader a basic understanding of the EU proposed concept method, an overview of the CNOSSOS-EU is provided in the next section. Next, the theoretical concept of the Nord2000 model is discussed.

2.3 CNOSSOS-EU model

According to CNOSSOS-EU, the road traffic noise source is determined by combining the noise emission of each individual vehicle that forms the traffic flow (Kephalopoulos et al., 2012). These vehicles are classified into four categories based on their noise emission characteristics, Light motor (1), Medium heavy (2), Heavy vehicles (3), and Powered two-wheelers (4). Each vehicle is defined as a point source of noise, and it is positioned 0.05 metres above the road surface (Figure 2.2). Traffic flow noise emissions are represented by source lines characterized by directional sound power per meter per frequency. CNOSSOS-EU separates calculations for rolling noise (due to the tyre and road interaction) and propulsion noise (produced by the driveline e.g., engine, exhaust, etc.) of the vehicle (cf. section 2.2.2).

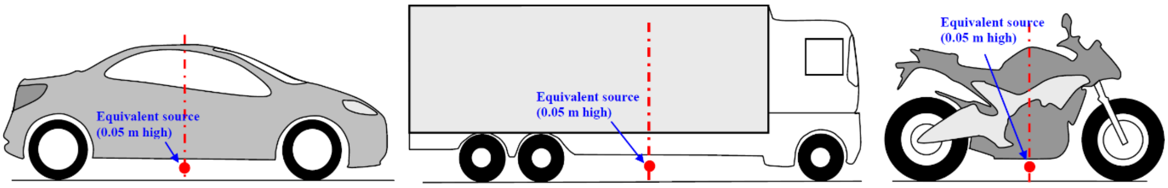

Figure 2.2 - Location of the corresponding point sources on light vehicles, medium & heavy vehicles as well as two-wheelers (Kephalopoulos et al., 2012)

For light, medium, and heavy motor vehicles (categories 1, 2 and 3), the sound power corresponds to the energetic summation of the rolling and the propulsion noise. Thus, The mathematical expression for the sound power level emitted by one of the sources rolling or propulsion ($L_{W,i,m}$) for m=1, 2 or 3 is defined by Equation 2.8 (Kephalopoulos et al., 2014):

$$L_{W,i,m}(v_m) = 10 \times log\left(10^{L_{WR,i,m}(v_m)/10} + 10^{L_{WP,i,m}(v_m)/10}\right) \tag{2.8}$$

$L_{WR,i,m}$ is the sound power level for rolling noise and $L_{WP,i,m}$ is the sound power level for propulsion noise. The vehicle speed v_{m} is 20 km/h ≤ v_{m} ≤ 130 km/h. Sound power levels are calculated for each octave band i from 125 Hz to 4000 Hz. For two-wheelers (category 4), only propulsion noise is considered for the source line, Equation 2.9:

$$L_{W,i,m=4}(v_{m=4}) = L_{WP,i,m=4}(v_{m=4}) \tag{2.9}$$

The Equations 2.8 and 2.9 are valid under meteorology and traffic reference conditions such as constant vehicle speed, flat road, air temperature τ_{ref} = 20 °C, virtual reference road surface (consisting of an average of dense asphalt concrete 0/11 (11 mm aggregate size) and stone mastic asphalt 0/11, between 2 and 7 years old and in a representative maintenance condition), dry road surface, vehicle fleet for which the characteristics correspond to the values found for the European average, no studded tyres. To correct these assumptions, several conditions are taken into account in the CNOSSOS-EU road traffic noise model. The mathematical calculations are available in (Kephalopoulos et al., 2012).

2.4 Nord2000 model

Nord2000 is a Nordic noise propagation simulation model first developed in 1996-2001 on the initiative of the Nordic Council of Ministers. It uses the results of research and development that have taken place since the publication of the first common Nordic methods in the 1970s and early 1980s. The method includes source models for road and rail traffic in the third-octave band from 25 Hz to 10 kHz. Nord2000 is suitable for calculating different weather conditions, helping to accurately calculate different types of noise levels and determine the average annual noise level (Kragh et al., 2002).

The prediction method separates tyre/road noise from propulsion noise as discussed in section 2.2.2. It is also possible to calculate the effect of studded tyres and of vehicle acceleration and to correct the tyre/road noise generation for variation in air temperature. The method distinguishes between medium heavy and heavy vehicles and introduces the number of axles (8 axles) of heavy vehicles as an input parameter.

The prediction method can handle any number and any combination of varying ground conditions, both with and without barriers. The algorithms have been limited to two types of obstacles. The barriers can be thin or thick in any shape.

For any type of road vehicle, Nord2000 Road can be applied to calculate L_{eq}, either overall A-weighted or in frequency bands, as long as input data are available. By combining the results of different meteorological conditions, it is possible to calculate the annual average noise levels such as L_{den} and L_{night} specified in the European directive. L_{den} is calculated using Equation 2.7 (Kragh, 2011a).

The model is based on geometrical ray theory and theory of diffraction and calculations are performed in one third octave bands.

Nord2000 propagation model is based on geometric ray theory and the screen calculation is based on geometric diffraction theory. An overview is provided in section 2.4.1.

2.4.1 Propagation model

The sound propagation model (Plovsing & Kragh, 2006) in Nord2000 is based on geometric ray theory and provides an algorithm to calculate the sound attenuation over 1/3 octave band along the source path S to the receiver R with respect to the topography and the ground type (acoustic impedance). The model includes contributions from all terrain segments to the resultant ground and screen effect when the vertical terrain cross-section is reduced to a series of straight-line segments, as shown in Figure 2.3(a).

Nord2000 makes advantage of Fresnel zones[2] for ground effect, Figure 2.3(b). The advantage is that the ground effect is computed for each type of ground that may be found inside the Fresnel-zone. The ground effect that results is then calculated as a weighted average taking into consideration the fraction of the Fresnel-zone covered by each type of ground type. This helps in resolving issues with discontinuity in computing results. For more information regarding Fresnel zone see Hothersall and Harriott (1995); Kragh et al. (2002); Plovsing (2007).

Eight classes of the ground surface have been defined, ranging from very soft (moss-like) to very hard (dense asphalt or cement concrete). For noise mapping, normally only two classes: “soft” and “hard” are used. Each class is characterized by a representative flow resistivity (Appendix III (Kragh et al., 2006)). Terrain data may be entered “manually” into single-receiver software or imported from Digital Terrain Models into “automatic” mapping software. With the complexity of the Nord2000 model “manual” calculation is out of the question (Kragh, 2011a).

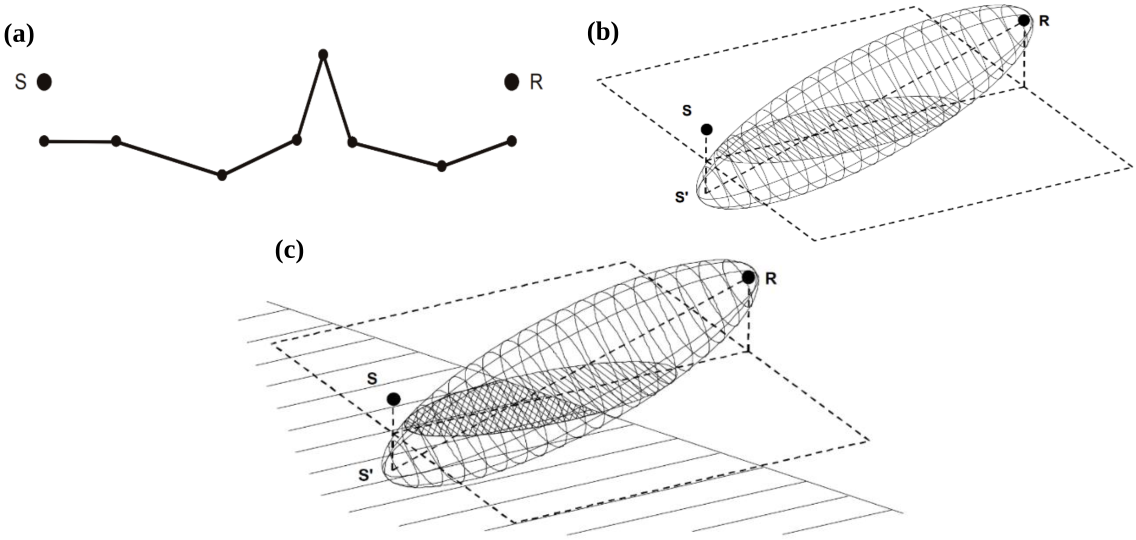

Figure 2.3 - (a) Vertical terrain cross-section simplified to straightline segments (Plovsing, 2006a) (b) Fresnel-ellipsoid and (hatched) Fresnel-zone for homogeneous ground surface (Plovsing & Kragh, 2006) (c) Fresnel zone in the event of a change in ground type (Kragh et al., 2002).

2.4.2 Nord2000 input data specifications

In Nord2000 Road vehicles are represented by noise sources located/placed at different heights (0.01 m, 0.30 m, and 0.75 m). The sound power level of each source is calculated using an equation with user-selected input parameters. The sound power contributions are derived from tyre/road noise and propulsion noise. Heavy vehicles with high exhaust have an additional source at 3.5 m height. The horizontal position of all sources is presupposed to be at 1 m from the vehicle centre line, in the direction of the receiver (Kragh et al., 2006).

The vehicle categories in Nord2000 are mainly divided into three categories, (1) light, the vehicles with length less than 5.5 m and weight 3500 kg, (2) medium, the vehicles with length between 5.6 to 12.5 m, weight 3500-12000 kg and 2 axles with 6 wheels, and (3) heavy, the vehicles with length more than 12.5 m and weight more than 12000 kg. In a more detailed

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[2] A Fresnel zone is one of many confocal elongated ellipsoidal zones of space located between and around a source and a receiver. The main wave will travel in a rather straight line from the source to the receiver.

division, heavy vehicles are divided into 6 categories from 3 axle to 8 axles. Depending on their characteristics, additional information should be defined in the model. In this way, the proportion of each vehicle categories (or the number of cars per category per unit time) should be specified for different type of roads.

Another input parameter for Nord2000 Road is the average vehicle speed per category. Table 2.3 illustrates the predefined average velocities that can be changed by specifying the actual average velocities. An additional input parameter for Nord2000 Road is the number of vehicles or the percentage of the traffic (per category, per lane when needed) during the day, evening, and night. The definition of day, evening and night for Nordic countries is available in Table 2.1. There are default data in this situation as well and can be substituted by user data.

In aspect of road surface, there are some parameters for correction tyre and road noise sound power levels. For achieving this correction $\Delta L_{surface}$, the following corrections should be considered.

- Average of dense asphalt concrete (DAC 11) and stone mastic asphalt (SMA 11) with maximum aggregate size 11 mm, at an age of more than 2 years, but not at the end of its life span
- Air temperature: 20ºC
- Country: DK (FI, NO, and SE have an additional road surface correction).

Table 2.3 - Different types of roads based on Nord2000 definition and predefined average vehicle speed for each category (Kragh et al., 2006).

Traffic case	Description	Speed [km/h]		
		Cat. 1	Cat. 2	Cat. 3
A	Motorway 100-130 km/h	120	90	90
B	Urban motorway	90	85	85
C	Main road 80-90 km/h	85	75	75
D	Urban road 60-70 km/h	70	65	65
E	Urban road 50 km/h or feeder road in residential area	50	50	50
F	Residential road 30-40 km/h	35	35	35

The road surface influences sound propagation; hence its acoustic impedance is required. For each type of road surfaces, acoustic impedance should be determined. When no better information is available, the model provides default values. Flow resistivity (kPas/m^2) for very hard road surface, normal road and ISO surface are 200,000, 20,000, 2,000, respectively (Appendix III) and for porous road, Hamet model is implemented (Hamet & Berengier, 1993).

For computing receiver (point) height, Nord2000 follows END (Directive, 2002). As a result, the computation receiver height is the height above the local terrain. However, it can be changed according to each country's guidelines. But totally, (1) the receivers can be considered 4 m above ground in outdoor noise simulation (2), 1.5 metres above ground is the recommended height for use in locations with one-story homes and recreational areas. On the other hand, for assigning receivers to buildings 0.1 metres in front of the façade is recommended by European Commission (2006).

2.5 Comparing CNOSSOS-EU and Nord2000

Nord2000 considers parameters in more detail than CNOSSOS-EU. So, the disparity in results could be related to differences in CNOSSOS-EU and Nord2000 parameterizations e.g., handling of diffraction, refraction (Khan et al., 2021). Khan et al. (2021) compares three road traffic noise prediction models, CNOSSOS-EU, Nord2000 and TRANEX with more than one hundred test cases (N = 111, similar geographical characteristics). Considering CNOSSOS-EU and Nord2000, there are some differences and similarities in sources input data and also the results of the model (Table 2.4).

Table 2.4 - Comparison of CNOSSOS-EU and Nord2000 model (Khan et al., 2021)

	Nord2000	**CNOSSOS**
	Source modules	
Bands	1/3 Octave	Octave
Frequency range (Hz)	25- 10,000	63- 8000
Reference speed (km/h)	70	70
Speed range (km/h)	30-130	20-130
Road gradient (s) (%)	Correction of propulsion noise (s= 0-20)	Correction of propulsion noise (s= -6 to +20)
Reference temperature (°C)	20	20
Source height (m)	0.01, 0.30, 0.75, 3.5	0.5
Rolling noise	$A_R+B_R \log(v/v_{ref})$ *	$A_R+B_R \log(v/v_{ref})$
Propulsion noise	$A_P+B_P ((v- v_{ref}) / v_{ref})$ *	$A_P+B_P ((v- v_{ref}) / v_{ref})$
Noise emissions	Sound power coefficients (A_R, B_R and A_P, B_P)	Sound power coefficients (A_R, B_R and A_P, B_P)
Correction for road surfaces	Yes	Yes
	Result of the propagation modules	
Meteorological conditions	25 meteorological classes based on logarithmic and linear weather coefficients (includes relative humidity)	Homogeneous and favourable conditions
Maximum S - R path length (m)	1000	2000
Receiver height (m)	1.5 - 4	2 - 4
Geometrical divergence	$10 \log (4\pi d^2)$ $d = d_{Source} - d_{Receiver}$	$20 \log (d) + 11$ $d = d_{Source} - d_{Receiver}$
Reflections	Multiple reflections from building façades as well as reflections due to ground and noise screens	Multiple reflections from building façades as well as reflections due to ground and noise screens
Ground effect	Use of ray theory, Fresnel zones, and Chien and Soroka model. Coherence factors are defined for effects from scattering zones, frequency band averaging, turbulence, fluctuating refraction, surface roughness etc.	Use of mean ground plane, acoustic characterisation of ground, and several atmospheric conditions. Computed by interference between the reflected and the propagated sound
Diffraction effect	Use of Hadden-Pierce ray and Salomons approaches for single and multiple screens. The former approach makes further use of the Jonasson image method with diffraction	Division of propagation path at source and receiver sides with respect to point of diffraction. For each side, path difference and ground effects are calculated

* A_R, B_R = rolling noise coefficients; A_P, B_P = propulsion noise coefficients;
v = instantaneous vehicle speed; v_{ref} = reference vehicle speed

In a general sense, the Nord2000 and the CNOSSOS-EU are advanced because they are fully based on physics. The propagation model adopted in CNOSSOS-EU is based on the French NMPB 2008 method and was considered good enough for strategic noise mappings through EU MS. (Note: in general, strategic (global) noise mapping differs from detailed (local) noise mapping for action planning.) (Zhang, 2014). Dissimilar to CNOSSOS-EU, Nord2000 models can be used for noise prediction in more complex situations. Nord2000 uses 1/3 octave bands, advanced outdoor propagation models, and more vehicle and ground categories (Larsson, 2016).

Gustafson & Genell shows that CNOSSOS-EU calculations underestimate L_{den} with up to 8 dB in comparison with NORD2000 using realistic weather statistics (Andreas Gustafson & Anders Genell, 2021; Peeters & van Blokland, 2018). The reason is likely the different meteorological approaches in the two models,

2.6 Noise modelling tools

Noise mapping platforms and noise simulations can be investigated both outdoors and indoors. In the outdoor situation, it is considered that the noise reaches the open window in a building and the person inside the building can hear the noise directly. Also, according to END the distance of 4 m in front of the building must be defined in noise simulation. In indoor situation, all the factors that influence the production of noise in the interior of the room are measured. The noise that enters the room from the window and from the façade of the building can be controlled with a suitable design of the building especially in big cities and areas with heavy traffic. One of the measures is to use a double-glazed window. The use of double-glazed windows and doors increases insulation performance considerably. This study is focusing on outdoor noise simulations exclusively.

Meller et al. (2022) conducted a literature review over 63 articles to select the optimum software for noise mapping in academic studies. They have concluded that most of the studies utilized SoundPLAN and ArcGIS software. SoundPLAN software specializes in computer simulation of noise and air pollution situations. On the other hand, Carr et al. (2011) made a comparison among STAMINA 2.0, STAMSON 5.1, TNM 2.5 (Traffic Noise Model), Cadna/(A)coustic and SoundPLAN software, the results of which can be seen in Table 2.5.

The classification seen in Table 2.5 was presented at the Noise Conference[3] in the Canadian acoustical association, 2012. The purpose of this project (Carr et al., 2011), which was funded by the Ontario Ministry of Transportation, was to discover a model that met Ontario's criteria. STAMSON 5.1 and STAMINA 2.0 are both free but have a high score in other classifications. TNM has average score in most categories except low score in hardware and high score in speed category. Cadna/A is expensive and has low scores in most categories. SoundPLAN has low scores in most categories, including hardware requirements, probability, speed, customization, and import data.

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[3] https://donald-cudmore.squarespace.com/s/09SPentonRoadNoiseModeling.pdf

Table 2.5 - ranking of sound modelling software. With a score of 1, the best result is indicated, and a subsequent number indicates a drop in standing from the one before it.

	Cost	**Ease of use**	**Hardware**	**Portability**	**Input**	**Update**	**Speed**	**Customization**	**Import**
STAMSON 5.1	1 free	4	4	5	4	5	3	5	4
STAMINA 2.0	1 free	5	4	4	5	4	4	4	4
TNM	3	3	1	3	3	3	5	3	3
Cadna/A	5	1	1	2	1	1	2	1	2
SoundPLAN	4	2	1	1	2	2	1	1	1

Ease of Use: Pros include GUIs, 3D views, batch processing. Cons include limits on inputs (no. of receivers / no. of sources), documentation, options.
Hardware: STAMINA and STAMSON do no run-on 64-bit machines.
Portability: Ability to export between packages.
Input: Ability to easily add data. Ease of use of GUI, text files, etc.
Update: Ability to copy and modify runs, ability to run multiple barrier heights in single runs.
Speed: Time required for calculation runs.
Customization: Ability to add custom sources not included in the database.
Import: Ability to import data from other software packages (bitmaps, cad drawings, files from other modelling packages).

2.6.1 SoundPLAN

SoundPLAN GmbH[4] is a software company based in Germany that specializes in noise prediction, noise mapping, and noise control software. The company was founded in 1984 and has since become a leading provider of noise simulation software. SoundPLAN software is used by engineers, planners, and acousticians worldwide for a variety of applications, such as environmental impact assessment, transportation noise analysis, and urban planning. The company offers a range of software products, including SoundPLAN Essential, SoundPLAN Model, SoundPLAN Air, and SoundPLAN Noise Mapping. SoundPLANnoise can model and simulate noise in outdoor environments. Furthermore, the company provides more software for noise simulation of room acoustics (Sarooma) and Environmental Impact Assessment (EIA) in industrial environments (SoundPLANmanda).

SoundPLANnoise consist of many simulation models e.g.: Road noise, Railway noise, Industry/Parking lot noise, Aircraft noise and Wind turbine noise. Some examples of noise simulation model for roads are RLS-90, BUB:2018, RVS 04.02.11:2019, sonROAD18, CoRTN:1988, RTN:1996, Nord2000 Road, NMPB2008, TNM 3.0 and CNOSSOS-EU, etc. Data and layers can be imported as DXF, ESRI shape files, CityGML, OpenStreetMap, the QSI interface via the free programmable ASCII interface. Also, it can be possible to digitise the paper maps in bmp, tif, jpg and png file formats. All imported objects in Geo-Database are stored in Geo-files and can be managed in Situations. The flowchart in Figure 2.4 shows the main ways to organize small projects.

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

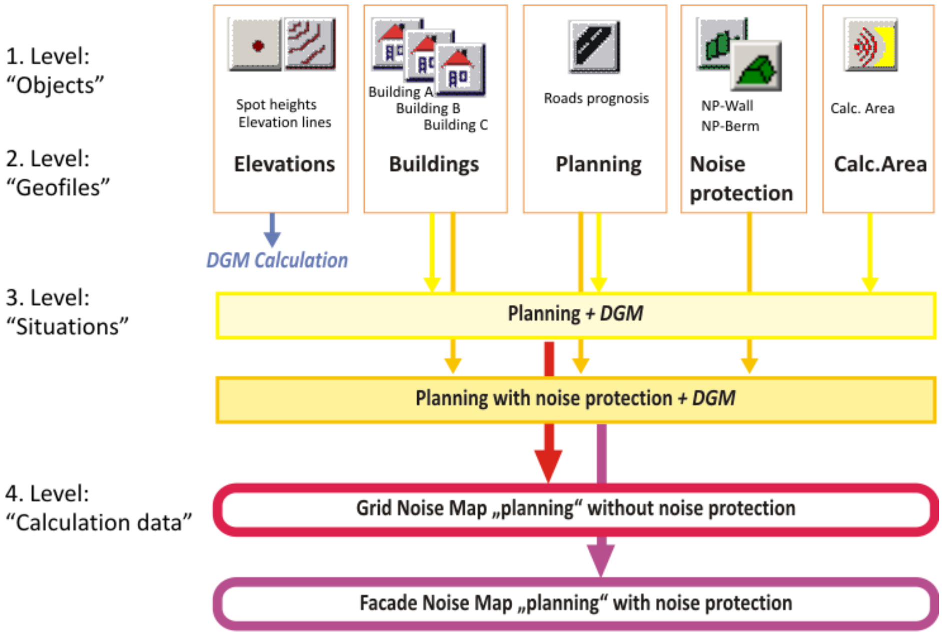

Figure 2.4 - to obtain a façade noise map in SoundPLAN, save the relevant Objects as Geofiles and then categorise them into Situations. A different Digital Ground Model can be defined for each Situation based on Objects. The fourth step is to compute the noise map of the building's façade (SoundPLAN, 2020).

Now that the theory of noise propagation and some background on noise simulations have been covered, the next chapter deals with an introduction to 3D city model input data formats. The 3D city model data of the study area is available in CityGML format.

2.7 Sensitivity analysis based on façade material

Sensitivity analysis of input data for noise simulation is a critical aspect that needs to be considered to obtain accurate results, a noted in Chapter 1.

In the context of preparing road traffic noise maps, it may be feasible to investigate the impact of different materials used in building façades on noise propagation. Examples of materials to consider include brick, plaster, wood, concrete, aluminium, and glass. Research conducted by Eggenschwiler et al. (2022) highlights the importance of considering type of façade in mitigating the impact of road traffic noise. The results of the study showed that the perceived noise annoyance in inner courtyards is influenced by various factors, including façade characteristics, building orientation, and noise exposure. The study found that noise annoyance was lower in courtyards with building façades that had noise-reducing elements such as balconies and awnings. The presence of greenery and open spaces in the courtyards was also found to have a positive impact on noise annoyance reduction. Moreover, Fediuk et al. (2021) provides an overview of the acoustic properties of different types of concrete, while Wong et al. (2010) demonstrate that the vertical greenery systems had the potential to reduce noise levels by improving sound insulation and absorption. This could be done by examining the absorption and reflection coefficients and reflection loss of different building façade materials and their impact on noise propagation. The values of these parameters depend on various factors, including the frequency of the sound wave, the angle of incidence, and the surface condition of the material. An extensive list of absorption coefficients α of building materials and finishes is available in Sengpiel (n.d.).

The reflection properties (the reflection loss RL, absorption coefficients α and reflection coefficients ρ) are dependent on the material of the wall. By inputting a single value, it is possible to derive the other two values through calculation. These values can be changed manually, and this adds the possibility for user-defined parameters. Reflection loss is defined by Equation 2.10.

$$\mathrm{RL} = -10\log_{10}|\rho| \tag{2.10}$$

RL expressed in dB, and $\alpha+\rho=1$ (Fuchs & Möser, 2013).

"Reflection loss" refers to the reduction in sound energy due to the reflection of sound waves from a surface. SoundPLAN considers the reflection loss from all surfaces in the environment, such as buildings, walls, and other obstacles, to predict the sound levels at different locations. The magnitude of the loss depends on the material of the wall, the impact angle, the frequency, and the size of the wall or building. For sound-reflecting surfaces, a reflection loss of 1.0 dB per reflection is generally assumed (corresponds to an absorption factor, α, 0.21 and reflection coefficient, ρ, 0.79).

According to the Nord2000 model, the default setting for energy reflection coefficient is given in Table 2.6, unless more accurate data are available (Kragh et al., 2006).

Table 2.6 - energy reflection coefficients (ρ_E), $\rho_E=0.8$ is generally assumed for building façade (Kragh et al., 2006).

Characteristics of reflecting surfaces	ρ_E
Plane and acoustically hard surface (concrete, stone, brick wall, metal sheets)	1.0
Non-absorbent building façade with windows and small irregularities, dense wooden panels	0.8
Factory walls with 50% of the surface consisting of openings, installations, or pipes	0.4

3 3D city models as input data to noise simulation

A 3D city model is a digital representation of a city that incorporates three-dimensional geometric data to visualize and analyse urban environments. It includes information about the geometry, topology, and appearance of buildings, roads, and other urban features. A semantic 3D city model goes beyond this by adding semantic information to the model, such as the function of buildings, their age, and their accessibility. This type of model provides valuable information for urban planning, environmental assessment, and disaster management. One of the most widely used formats for semantic 3D city models is the CityGML standard, which defines a common data model and XML-based encoding for the representation, storage, and exchange of 3D urban objects and their attributes. It was developed by the Open Geospatial Consortium (OGC)[5]. CityGML supports different levels of detail and can be used for a wide range of applications, including visualization, simulation (e.g., daylight simulations, flood simulations, noise simulations etc.).

3D city models are commonly used as input data for noise simulations because they provide a comprehensive representation of the urban environment (Biljecki et al., 2015; Chen, 2011; Saran et al., 2018). The models contain information on the location, height, and geometry of buildings, as well as other objects such as trees, roads, and bridges. This information is crucial for accurate noise predictions, as it allows the noise propagation to be modelled more realistically. The sound pressure levels at different points in the area can be calculated using 3D city models as input by noise simulation software, enabling for the assessment of noise impacts from different sources such as traffic or industrial activities.

This chapter explores the use of 3D city models as input data for noise simulation. In section 3.1, the chapter discusses the geodata required for noise modelling, including building geometries, terrain data, and other relevant features. Section 3.2 explores CityGML. The section discusses the various versions of CityGML available, including CityGML 2.0 in section 3.2.1 and the CityGML Application Domain Extensions (ADE) in section 3.2.2. The chapter also covers the CityGML noise ADE (section 3.2.3), which provides noise-related data in 3D city models. Section 3.3 focuses on the Swedish 3D city model specification 3CIM. Section 3.3.1 discusses the specifications in detail, including the level of detail available in the model. The section also covers the advantages and limitations of 3CIM as input data for noise simulation. Section 3.4 discusses how the height of buildings are calculated in simulation software.

3.1 3D geodata required for noise modelling

Creating a noise map requires providing corresponding input data and storing this data in a defined database. In urban areas of European Union Member States, the implementation of the Environmental Noise Directive (END) 2002/49/EG for noise mapping creates many demands for the access, availability, and integration of multiple thematic and geographic information. Spatial Data Infrastructure (SDI) techniques are used to facilitate noise mapping (Czerwinski et al., 2006b). The European Union's Spatial Data Infrastructure (INSPIRE, 2007) and the END provide data management principles for the standardization of data formats among member states. Therefore, the END and INSPIRE provide important directives for managing noise data

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[5] https://www.ogc.org/standards/citygml

and ensuring that noise mapping is carried out efficiently and accurately across the European Union.

The INSPIRE aims to establish a framework for the creation, management, and sharing of geospatial data across member states. The INSPIRE directive is separated into the following legislative components: metadata, network services, interoperability of geographic data sets and services, data exchange, monitoring, and reporting (Abramic et al., 2017). INSPIRE employs international standards as the foundation for the European interoperability infrastructure; as a result, each country with its own national system improves the value of its existing systems by harmonising them through the use of INSPIRE. A substantial portion of the standards utilised in INSPIRE are developed by the OGC and the International Standards Organization (ISO).

The INSPIRE has identified two relevant themes for conducting noise simulations. The first theme is Environmental Monitoring Facilities which provides data on measurement and monitoring facilities for environmental parameters such as noise (INSPIRE, 2013a). It includes information on the location, status, and availability of monitoring stations, as well as the type and quality of measurements being taken. The second theme is Land Use (INSPIRE, 2013b) which provides data on the location and characteristics of buildings, roads, railways, airports, and other sources of noise. It also includes data on the spatial extent of natural and semi-natural areas such as forests and wetlands, which can affect the propagation of noise. These two themes provide the necessary information to conduct noise simulations by providing data on the sources of noise (e.g., roads, railways, airports), the receivers of noise (e.g., buildings), and the environmental conditions that affect the propagation of noise (e.g., topography, land cover, and atmospheric conditions). These INSPIRE themes are based on CityGML. Therefore, CityGML can be seen as one of the technical standards used by INSPIRE to enable the interoperability and exchange of geospatial data related to buildings and other urban features (Czerwinski et al., 2007; Gröger et al., 2012).

By using CityGML, it is possible to represent data on land use and environmental monitoring facilities, as well as 3D geodata such as digital ground models (DGM), 3D building models, and noise barriers (Arroyo Ohori et al., 2018; Gröger et al., 2012).

3.2 CityGML

CityGML was originally developed by the members of the Special Interest Group 3D (SIG 3D) who were part of an initiative Geodata Infrastructure North-Rhine Westphalia (GDI NRW) in Germany. However, it is presently an open standard developed and maintained by the OGC. CityGML utilizes an XML-based format for storing and exchanging semantic information related to 3D building models, while geometries are stored in GML3 (Geography Markup Language 3). GML3 is an international standard for geodata exchange of the OGC and the International Organisation for Standardisation (ISO TC211) (Cox et al., 2004; Czerwinski et al., 2006b; Kolbe et al., 2008).

Homogeneous descriptions in CityGML include both semantic and geometric information, providing comprehensive details about the meaning, interpretation, and spatial attributes of 3D objects, thus ensuring consistency throughout their representation (Gröger et al., 2012). The semantic information refers to the meaning and function of an object in the urban context, such as its building type, use, or function. The geometric information refers to the physical characteristics of an object, such as its shape, size, location, and orientation. This allows for data storage and retrieval, as well as easier analysis and processing of the data. These descriptions include classification and aggregation of various elements such as, buildings, bridges, tunnels, vegetation, water bodies, transportation, and city furniture. The goal of developing CityGML is to achieve a common definition of the basic entities, attributes, and relationships of 3D city models, allowing the reuse of the same data in different application fields.

CityGML has officially been released in three versions. The first version, CityGML version 1.0, was released in 2008, followed by CityGML version 2.0 in 2012. CityGML 2.0 introduced several enhancements such as support for different coordinate reference systems, a more flexible representation of geometry, and improved support for different application domains through the use of ADEs. CityGML version 2.0 also introduced several improvements and new features, including support for tunnels, bridges, and vegetation. The latest version, CityGML version 3.0, was released in 2020 and introduces several new concepts and features (Kutzner et al., 2020; OGC, 2021). It includes a modular structure which allows for better customization and interoperability with other standards. It also includes new features such as support for subsurface structures, dynamic objects, and improved support for indoor models. Additionally, CityGML version 3.0 has a new metadata model that provides better documentation and management of 3D city models.

3.2.1 CityGML Core Module

CityGML consists of a core module and thematic extension modules (Gröger & Plümer, 2012; Kolbe et al., 2008). The CityGML Core Module defines the basic concepts and components of the CityGML data model. The following 13 thematic extension modules were introduced in version 2.0 of the CityGML standard: Appearance, Bridge, Building, CityFurniture, CityObjectGroup, Generics, LandUse, Relief, Transportation, Tunnel, Vegetation, WaterBody, and TexturedSurface [deprecated]. As the CityGML data model is thematically divided, implementations can support any number of extension modules in addition to the core module and yet be considered CityGML compliant. The extension modules can therefore be combined in accordance with the information requirements of a certain application or application domain. The term "CityGML profile" refers to a collection of modules. The CityGML basic profile is the result of adding all the modules together. Each module has the ability to import namespaces linked to other relevant CityGML modules based on dependency relationships between modules. Each CityGML module is defined within a distinct and globally unique XML target namespace and is described by its own XML schema specification file. In Figure 3.1, a UML (Unified Modelling Language) package diagram is used to show the interdependencies between the modules of CityGML. Each module is represented by a package. The package names match to the module names.

These modules provide 3D geodata, however, there are specific details for noise simulation that cannot be described in CityGML. Therefore, the ADE is utilized to develop extensions to the CityGML data model that relates to certain application fields, as outlined in the next section.

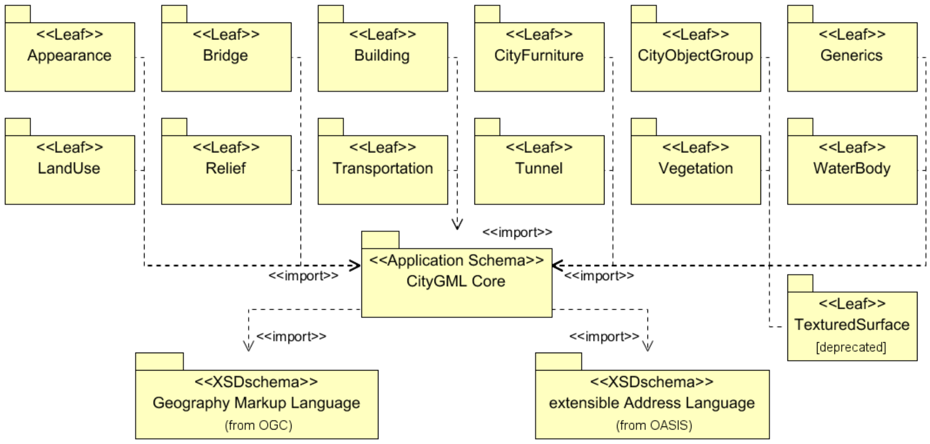

Figure 3.1 - CityGML individual modules and their relationship to one another are shown in a UML package diagram (Gröger et al., 2012).

3.2.2 CityGML Application Domain Extensions

ADEs is a mechanism to enrich the data model with new feature classes and attributes while preserving the semantic structure of CityGML. Its main purpose is to support additional requirements under certain use cases, this is done by specifying extensions to the data model (Biljecki et al., 2018).

ADE specify additions for the CityGML data model. These additions include the introduction of new properties to existing CityGML classes, e.g., the number of inhabitants of a building or the definition of new object types. The difference between ADE and generic objects and properties is that ADE must be defined in an additional XML schema definition file with its own namespace. This file must explicitly import the XML schema definition of the extended CityGML modules (Gröger et al., 2012). In other words, each ADE is specified by its own XML schema file. The target namespace is provided by the information community who specifies the CityGML ADE.

The CityGML data model allows for flexibility in adding more information by defining ADEs for one or multiple CityGML modules. Biljecki et al. (2018) identified around 44 applications of ADE in CityGML, such as, energy ADE, noise ADE, robotics ADE, cadastre ADE, road traffic noise ADE, air quality ADE, GeoBIM, etc. ADEs have also been used for harmonisation of CityGML with national standards; for example, in the Netherlands (van den Brink et al., 2013) and Sweden (Uggla et al., 2023). The noise ADE is further discussed in the next section.

3.2.3 CityGML noise ADE

The Institute of Geodesy and Geoinformation at the University of Bonn, along with the Special Interest Group (SIG) 3D of GDI NRW (Geodata Infrastructure North Rhine-Westphalia), have developed a CityGML noise application schema using the ADE mechanism (Czerwinski et al., 2007). This method allows for the extension of the CityGML data model in supporting additional concepts required by specific use cases. The noise ADE is utilized to simulate environmental noise dispersion in accordance with the END directive (2002/49/EC).

The German noise immission computation rules[6,7] provide the semantics of the specific attributes and object types for CityGML Noise ADE. As an example, for road traffic noise simulation and calculation levels of noise, data such as Digital Terrain Models, 3D building models with their thematic attributes (e.g., reflection, inhabitants), 3D road data with their thematic attributes (e.g., traffic flow, heavy vehicle percentage, speed limit, type of road surface, road gradient, width of a road), 3D noise barriers and their thematic attributes (e.g., reflection) are required.

The CityGML Noise ADE data models are provided as UML diagrams and XML schema in figure Appendix IV (Czerwinski et al., 2007; Gröger et al., 2012).

3.2.4 Building theme

The focus of this study is to examine how various building materials react to simulated noise and to assess their sensitivity to it. When sound waves encounter a surface e.g., a wall or a building façade, a portion of the energy is reflected into the environment, and the remaining energy is transmitted through the surface (Section 2.7). The amount of reflection loss depends on several factors, including the angle of incidence of the sound wave, the absorption properties of the surface, and the frequency of the sound wave (Geng et al., 2021). Geng et al. (2021) conducted an experimental investigation to determine the reflection loss of various building materials, such as plasterboard, thick plasterboard, glass, heavy concrete, medium concrete, brick, metal, and wood, for different frequencies and angles of incidence. Acoustic properties that might be helpful for noise simulation, can be stored in noise ADE.

3.3 The Swedish 3D city model specifications 3CIM

3CIM (3D City Information Model) is a technical extension of the OGC CityGML 2.0 standard that has been implemented as an ADE (Uggla et al., 2023). 3CIM is a new Swedish standard for 3D city models developed in collaboration with the three major cities Stockholm, Gothenburg, and Malmö, along with Lund University. In general, the core of 3CIM is based on CityGML 2.0 and uses ADEs to extend the standard CityGML schema for specific application domains. 3CIM has adapted the themes, classes, and attributes of CityGML to better suit the needs of Swedish municipalities. 3CIM utilizes the class and function attributes from CityGML 2.0, but with their own code lists. However, the attribute usage, which is present in all themes of CityGML 2.0, has been excluded from 3CIM due to the inability of municipalities to keep track of the actual usage of objects (3CIM, 2022). The usage of objects can change rapidly, making it challenging to maintain accurate records. The exclusion of attribute usage from 3CIM does not necessarily mean that the information about them is lost. Municipalities can still collect and manage this information separately, and it can be used in conjunction with 3CIM data to provide a more comprehensive understanding of urban environments. Most topics in 3CIM correspond to specific modules in CityGML, but the utility themes are created from scratch in the ADE. 3CIM works with National Specifications (NS) and therefore uses the Lantmäteriet resource model for geometry resources[8]. The geodata is saved in the vertical coordinate system RH 2000 and the local Sweref 99 projections, which are implemented by municipalities.

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[6] https://www.gesetze-im-internet.de/bimschv_34/

[7] https://www.umwelt-online.de/recht/laerm/vbusch_ges.htm

[8] https://www.smartbuilt.se/projekt/informationsinfrastruktur/3cim/ (3CIM Version 2, pdf)

3CIM is not built on an ADE that is application oriented. This is because maintaining a semantically rich city model requires extensive work, including keeping the information up to date and compatible with the operational systems (e.g., building permit system, cadastre system). Instead, there is a semantically thin model within 3CIM that facilitates connectivity to multiple operational systems and external registers (e.g., the national road database, trees, and vegetation databases, etc.). Linkages between these systems and external data sets are implemented using the CityGML External References class. 3CIM does have an ADE, but it is primarily used to harmonize with national standards and adapt data to facilitate cross-referencing to external databases. For simple applications, 3CIM files can be read directly, but more demanding applications that need external data require additional steps to generate the input files (see Figure 3.2).

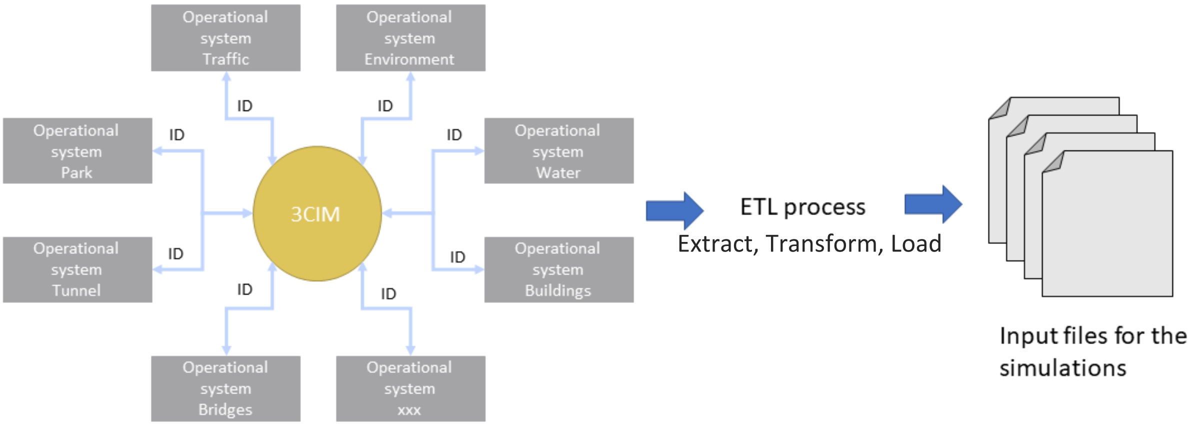

Figure 3.2 - 3CIM connects to external databases or operating systems (such as municipalities). Municipalities traditionally have operational systems for various activities designated by their ID. This approach requires a process to prepare input data for desired purposes like noise simulation (Uggla et al., 2023).

One of the complex themes are roads which are considered as sources of noise in traffic noise simulation. The Transportation theme in 3CIM refers to things that are related to transportation and the different surfaces that make up the roads. This theme is focused on meeting the needs of transportation and ensuring that the road infrastructure is suitable for noise modelling. To create this theme, CityGML 2.0 was modified and combined with rules and methodologies from CityGML 3.0's Transportation theme to maintain a connection with the National Road Database (NVDB) of the Swedish transport administration and other databases. It should be noted that the Transportation theme is not meant for line-based analyses like route optimization and, thus, does not include road links except for railway tracks. As a result, the endpoints of the lines used to build polygons will not correspond with the line features in the base map. To address this issue, only traffic areas with *car traffic* can be divided into sections. Currently, the unique road link ID from the NVDB can be manually added as an external reference to each TrafficArea with *car traffic*. In the NVDB, roundabouts are split into several road links (Figure 3.3b), whereas in the base 3CIM data, they are modelled as a single roundabout (Figure 3.3a). Furthermore, the Transportation theme in 3CIM includes features like narrow pedestrian areas and green spaces (AuxiliaryTrafficArea) that should be considered when deciding which features to include in the transportation theme (Figure 3.3c). The schema of the transportation theme can be found in figure Appendix V (Uggla et al., 2023).

An "AuxiliaryTrafficArea" refers to an area that is adjacent to or near a road and is primarily intended to be used by pedestrians or cyclists. This area typically consists of narrow paths that are used for walking or cycling and may also include smaller areas with trees and grass for aesthetic purposes. The term "AuxiliaryTrafficArea" suggests that it is an additional area that is not primarily intended for vehicular traffic but serves a complementary function to support the safe and efficient movement of pedestrians and cyclists. Noise simulation considers this area as a ground absorption area that can attenuate noise regarding the material of ground and define the impedance of ground. In the context of noise simulation, the ground surface in AuxiliaryTrafficArea is considered as an absorber of sound, and its effectiveness in attenuating noise depends on various factors such as the material properties (grass, trees, etc.) of the ground surface. The ground surface is a critical factor to consider in noise simulation as it can have a significant impact on the propagation and attenuation of sound waves.

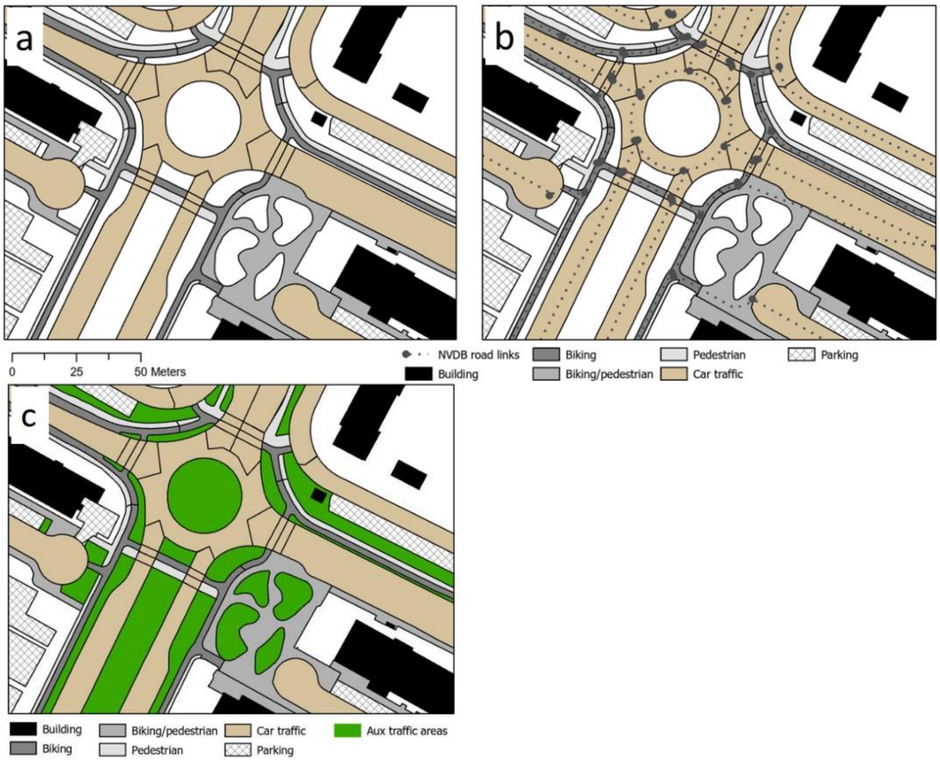

Figure 3.3 - the Transportation theme in 3CIM can be used to represent (a) traffic areas, as well as (b) road links from the National Road Database (NVDB). (c) Furthermore, the Transportation theme in 3CIM provides a way to segment TrafficArea and AuxiliaryTrafficArea into smaller parts based on their specific function, allowing for more accurate visualizations and area calculations. This segmentation method is taken from CityGML 3.0 but applied specifically to the Transport theme in 3CIM (Uggla et al., 2023).

The concept of Level Of Detail (LOD) involves partitioning themes into distinct subdivisions, with each subdivision presenting specific details. Section 3.3.1 provides more information about LODs.

3.3.1 Level of details in 3CIM

CityGML allows to store geometry at 5 LOD, ranging from LOD 0 to 4. LOD 0 has less detail than the geometry of the same urban scene in LOD 4. Biljecki et al. (2016) split and refine the LOD 0-3 into 16 different models (Figure 3.4). These divisions focus more on the exterior geometry of buildings, which provides a stricter specification and limits modelling freedom. It should be noted that LOD 4 is primarily focused on the building's interior, which is not presently considered for simulation of façade noise.

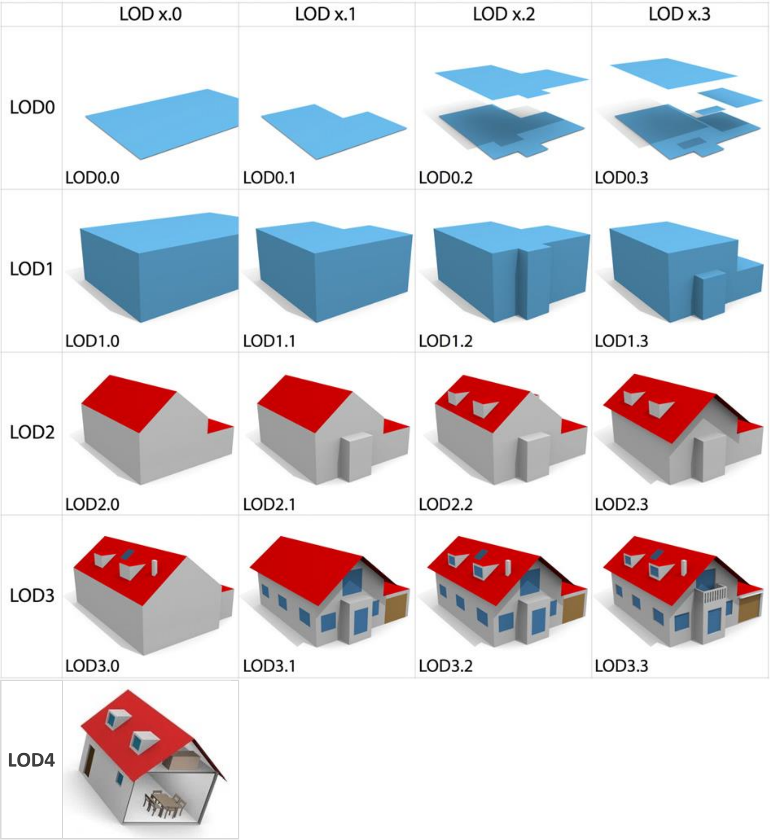

Figure 3.4 - the figure illustrates residential buildings that are divided into four distinct types for each LOD from 0 to 3. That results in a total of 16 sets of LODs. LOD 4 deals with the internal environment of the building. (Biljecki et al., 2016)

Building objects can be stored in 3CIM at any LOD level that CityGML 2.0 supports and defines. The *BuildingInstallations* class may be used to model objects and their geometries that are required for certain analyses and visualisations, such as downspouts and windows. A *BuildingInstallation* is an exterior component of a building that does not have the significance of a *BuildingPart* but has a direct impact on the building's outer attributes. Chimneys, stairs, antennas, balconies, or connected roofs, over steps, and paths are some examples (3CIM, 2022). The details of how the features are generally defined in 3CIM at various LODs are shown in Table 3.1.

The more detailed the representation of the objects like building façades (i.e., higher LOD), the better the sound can be simulated. However, getting more accurate information requires more time for preparing the information and executing the simulation, while it also increases the system requirements (e.g., RAM and processing power) for executing the simulation.

Table 3.1 - Features in the 3CIM project are divided according to the different types of LODs (3CIM, 2022).

Features	**Geometry and LODs**
Bridge	Bridges can be stored as solid bodies in LOD 1 or split into multiple surfaces in LOD 2. If LOD 2 is used, surfaces can be broken into OuterFloorSurface, Wallsurface or OuterCeilingSurface.
Buildings	3CIM enables storing building objects in any LOD level supported and defined by CityGML 2.0.
Utility (pipeline networks)	Well objects are stored as points in LOD 1. Overhead lines can be stored as multi lines in LOD 1 or LOD 2.
City Furniture	Ground details can be stored in 3 different LOD levels. Supported geometry types are solid, point, line, or surface. LOD 1: 3D point, 3D lines. LOD 2: 3D point with attributes describing extent, and 3D line with attributes describing extent, and Volume. LOD 3: ImplicitGeometry
Transportation	– LOD 0 Only used for railway tracks (Railway). Railroad tracks in LOD 0 are in 2D. – LOD 1 Used to describe the TransportationComplex as a multisurface. – LOD 2 Used to divide the road space into TrafficArea or AuxiliaryTrafficArea which together form the TransportationComplex in LOD 1. The geometry type is multi surface. – LOD 3 Used to divide TrafficArea and AuxiliaryTrafficArea into smaller parts depending on functionality. As a result, segmentation is better and can be used for e.g., area calculations or more accurate visualizations.
Tunnel	The tunnel body can be stored as a solid in LOD 1 (lod1Solid). The different sections of the tunnel, floor = FloorSurface and wall/ceiling = InteriorWallSurface, can be stored as multiple surfaces in LOD 2 (lod2MultiSurface) under CityGML 2.0.
Water body	Geometry is only stored in LOD 1 as a 3D multi surface according to CityGML 2.0.
Vegetation	Vegetation can either be solitary (SolitaryVegetationObject e.g., trees, häckar) or cover surfaces/volumes (PlantCover e.g., Grassland, Planting). Objects can either be in LOD 1 or LOD 2. The level of detail in the classification based on the 'function' attribute determines whether an object is categorized as LOD 1 or LOD 2.

3.4 SoundPLAN handling of building LODs

In SoundPLAN, LOD 2 CityGML data are automatically converted to LOD 1. Therefore, for calculating the average building heights of LOD 2, data are calculated from the heights of the roof areas (Figure 3.5). To determine the average building height for a particular roof area, both the average height and the swept floor[9] area are calculated. This is done for each roof area in the building. The resulting values are then used to determine the average building height based on the proportionate floor plan areas. The height of floors was considered as 2.5 m.

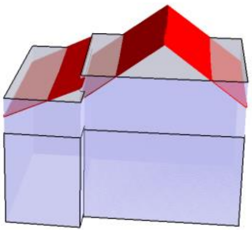

Figure 3.5 - a block building with heights calculated from the roofs and original surfaces, using LOD 2 data (SoundPLAN, 2020).

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[9] The area of the floor that is covered by the building above it.

4 Methodology

4.1 Background and workflow

This chapter provides a comprehensive overview of the methodology employed to conduct noise simulations, aimed at assessing the effects of road traffic noise on a specific study area. To achieve this objective, it was necessary to select software tools capable of managing and analysing spatial data and simulating noise propagation by processing the input data with efficiency. Furthermore, the evaluation of the impact of façade surface and roof on noise levels (L_{den}) was conducted.

The influence of the façade material (soft or hard) in the noise simulation was examined in this study, as discussed in section 2.7. Soft surfaces typically have a higher reflection loss value than hard surfaces, meaning that they absorb more sound energy and reflect less.

The research for this study covered buildings and infrastructure in the Lorensborg district in Malmö. It also considered the potential effects of densification on noise propagation. Therefore, the study included two separate scenarios for noise modelling: the current building structure and planned buildings. The latter refers to buildings that are not yet constructed but have been designed for the area. The workflow presented in Figure 4.1 is the process that the study follows to evaluate the impact of façade material and roof with different reflection loss on noise levels (L_{den}).

The methodology used in the study is presented, with details provided in six sections. The chapter begins by providing an overview of the study workflow as well as a motivation for the choice of tools (4.2). Then follows a description of the study area (4.3) along with a detailed presentation of the applied methodology (4.4-4.6). Section 4.6 outlines the parameters that are needed for the simulation model (4.6.1) and the method of distribution of receivers, which is an important aspect of the study as it determines where noise levels will be simulated (4.6.2). Section 4.6.3 focuses on determining the impact of different type of façade on the noise mapping results. Finally, the method adopted to account for the roof effect in the simulation is described (section 4.6.4).

4.2 Selection of tools and study workflow

GIS tools, FME (Feature Manipulation Engine), and SoundPLAN software are used for this study. GIS tools allow easy capture, store, manipulate, analyse, and present spatial data. FME enables the efficiently integrate and transform data from a variety of sources and formats. SoundPLAN software allows to model and predict L_{den}, which is a key component of this study.

GIS tools were chosen as the primary software to manage and analyse spatial data because they provide a powerful set of tools for data visualization and analysis, including the ability to identify patterns and relationships in the data. These tools were particularly useful for pre-processing the input data to ensure that it was in the correct format for further analysis.

FME Workbench 2022.2.2 was an essential software tool in this study, as it was used for data conversion/ transformation and processing. Specifically, FME was used to convert the CityGML datasets into ESRI shapefiles that could be imported into SoundPLAN software for further analysis.

Generally, FME offers a range of features for data handling and analysis. In addition to converting and integrating data, FME can be used to perform various data cleaning and processing tasks, such as removing duplicate data, restructuring data into a more manageable format, and performing calculations and statistical analyses on the data. These capabilities can be particularly useful in the context of noise simulation models, where accurate and reliable data are essential for producing meaningful results. Furthermore, FME offers a range of customization options, allowing users to tailor the software to their specific needs and requirements. For example, in this study, data such as vehicle flows and speeds in different time periods (day, evening, and night) were recalculated in order to provide the required data for calculating L_{den}.

Finally, SoundPLAN 8.2 software was used to simulate noise propagation based on Nord2000 model in the study area. This software provided the capability to simulate noise propagation from road traffic sources, as well as to generate noise maps and other relevant outputs. More information about SoundPLAN was written in section 2.6. The software also provides the option to select different calculation methods for noise propagation, allowing for customization based on the specific requirements of the study. Furthermore, SoundPLAN was provided with a free student licence by the company for this study.

An outline of the study's methodology is provided in Figure 4.1. The following is a description of the workflow steps:

(1) Input data: the available datasets are presented as a cylinder on the workflow. The datasets used in this study are Digital Elevation Model (DEM) in GeoTIFF format, road database, and a 3D city model (3CIM), section 4.4.

(2) Pre-process: GIS tools were used to prepare and analyse the datasets as well as visualization. GIS tools allowed to assess the CityGML data, evaluate the results generated by FME, and map the study area. FME is used to extract data from the 3CIM model. The output of FME is used as input data for noise simulation tool, section 4.5.

(3) Process: SoundPLAN was used to simulate noise levels in the study area. The chosen model for simulating noise was Nord2000. This model was employed to evaluate how the usage of different materials in the façade and roof influences noise levels (L_{den}). The necessary parameters for adjusting the model are presented in section 4.6.

(4) Result: The simulation results include two different scenarios, each with the aim of investigating the impact of building density in the area on noise levels. In the first scenario, current and planned buildings were considered, while the second scenario focused only on current buildings. Each of these scenarios was executed three times, with varying reflection losses of 0, 1, and 4 dB. As a result, a total of six sets of noise simulation data were generated.

As part of further investigation, a procedure was defined to examine how the noise level (L_{den}) is affected by the roof. GIS tools was used to compare and interpret the obtained results. The results are presented in Chapter 5.

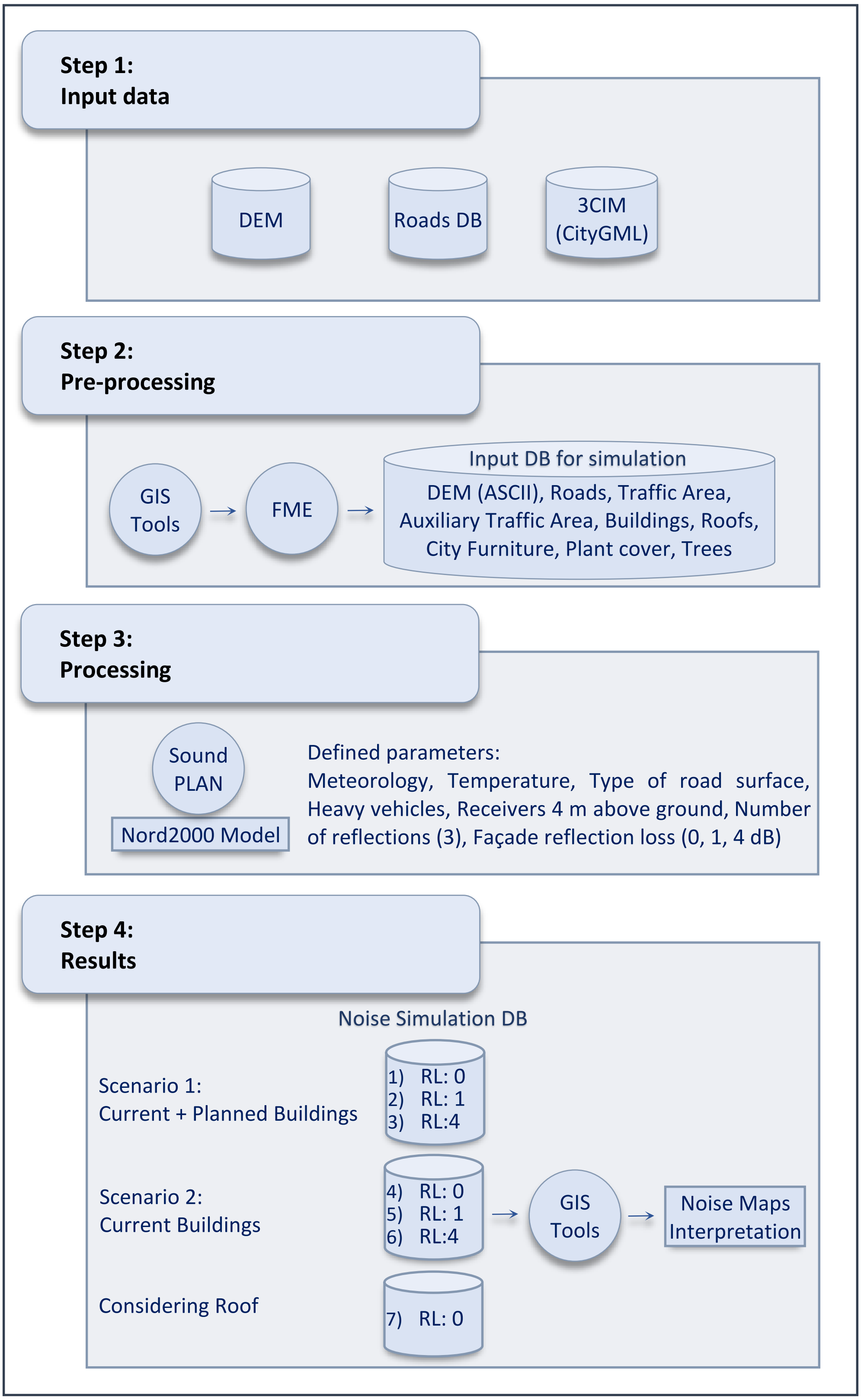


Figure 4.1 - this figure illustrates the workflow for the noise simulation model used in this study. RL: Reflection Loss (dB)

4.3 Study area

The study area for this research is located in Lorensborg, which is a district in the city of Malmö, Sweden, see Figure 4.2. Lorensborg is situated in the southwestern part of the city and is characterized by a mix of residential, commercial, and industrial areas. The area is densely populated, with a mix of high-rise and low-rise buildings. There are also several major and minor roads that run through the area, which can contribute to the overall levels of noise pollution.

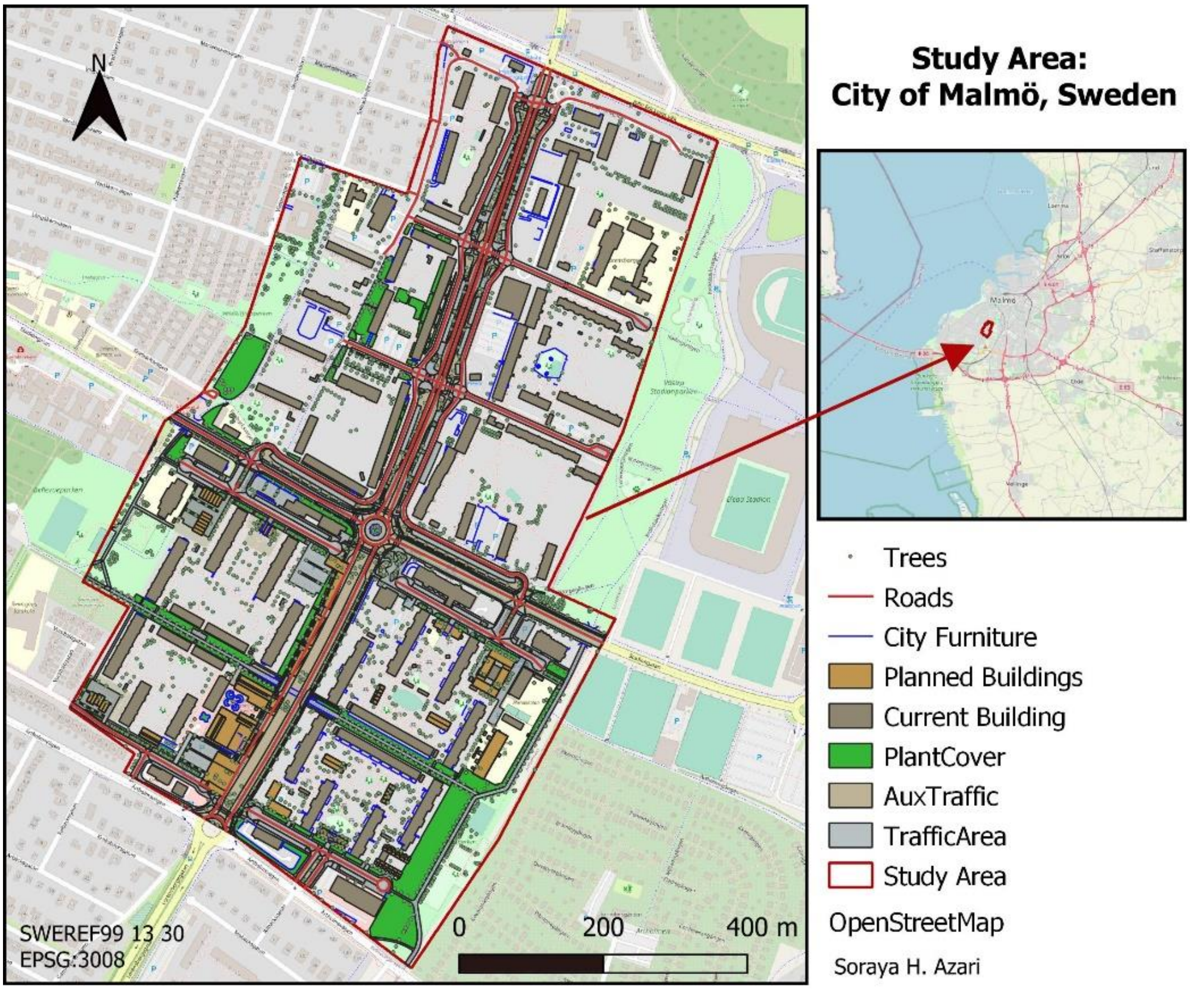
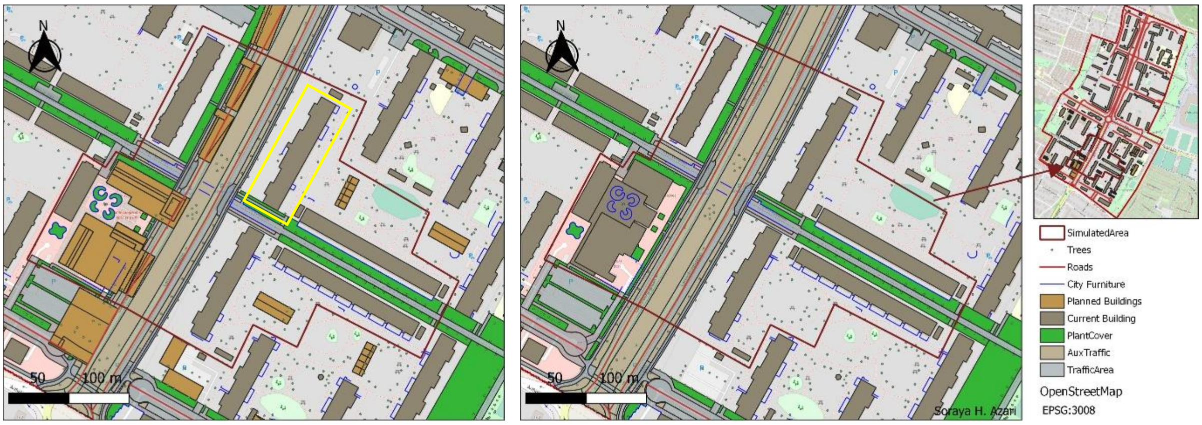


Figure 4.2 - this map shows a study area that is part of the city of Malmo, Skåne, Sweden

Lorensborg is a suitable study area for examining noise propagation in an urban environment, as it represents a typical urban district with a range of different land uses and noise sources. The required data for conducting noise simulation was imported for the study area depicted in Figure 4.2. However, due to the computational demands, the area under investigation was limited, as illustrated in Figure 4.3. For investigating the effect of the roof on the L_{den}, a simulation was conducted on the building that is shown by yellow rectangle in Figure 4.3.



Scenario (1) Scenario (2)

Figure 4.3 - two distinct map illustrating the simulated area for two different scenarios. Scenario (1): Current and Planned building, Scenario (2): Current building

4.4 Input datasets

In this study, several datasets were utilized as input data for the noise simulation models.

i. A Digital Elevation Model (DEM) with a resolution of 1m × 1m was obtained from Lantmäteriet, the Swedish mapping, cadastral and land registration authority.

ii. Road dataset was acquired from City of Malmö and contains data related to the flow of vehicles, including the number of cars, the speed of vehicles passing through, and the number of heavy vehicles. This Road dataset is used for both scenarios.

iii. The 3D city model (3CIM) was acquired from City of Malmö. These datasets provide information on the physical parameters of the buildings, roofs, traffic area, city furniture, and vegetation (plant cover and trees) including their location, height, and materials, which are important inputs for noise simulation models. The object classes which extracted and used in the study are *BuildingPart*, *RoofSurface*, TrafficArea, *AuxilirayTrafficArea*, *CityFurniture*, *PlantCover*, *SolitaryVegetationObject*.

4.4.1 Overview of the traffic noise source

The traffic patterns obtained from the Road dataset, which constitute a source of noise in this study, are presented in Figure 4.4. This figure provides information on the mean number of vehicles in 24 hours passing through on weekdays in 2020, based on data obtained from the Malmö municipality. Figure 4.4(a) illustrates the traffic patterns for the entire study area, while Figure 4.4(b) and Figure 4.4(c) respectively depict the case study area with planned and current buildings and their relationship with the roads. The analysis reveals that there is a greater concentration of traffic in the southern part of the study area. Through these maps, it was determined which parts of the road have affected the level of noise in the buildings.

Considering that the road information remains unchanged in both scenarios, it is important to highlight that the inclusion of the Planned buildings in scenario 1 will inevitably lead to an increase in the population statistics. This factor, however, has not been considered in this particular study, and it may impact the magnitude of traffic growth.

Figure 4.4 - road traffic load pattern. the average number of vehicles in 24 hours passing through on weekdays in 2020 (a) illustrates the whole study area, while (b) displays the planned and current buildings (scenario 1) and (c) displays just current buildings (scenario 2) and their proximity to roads in the case study area. In scenario 1, there are a few planned buildings that intersect with the existing roads. The proposed plan involves modifying the road layout to accommodate these buildings.

4.5 Pre-processing

The required themes were extracted from the 3CIM dataset using FME (Feature Manipulation Engine). FME was utilized for data processing. The first step involved using the *Reprojector* feature to transform the data from SWEREF99 TM to SWEREF99 13 30 coordinate system. Additionally, the *CoordinateSwapper* tool was applied to correct reversed latitude and longitude coordinates.

After importing the necessary data, several attribute adjustments were performed to meet the standards required for accurate noise simulation in SoundPLAN. These adjustments were based on the table in Appendix VI (Liu, 2023). Regarding vegetation (plant cover and trees), the classification of ground classes for plant cover was based on the Nord2000 code list and divided into two categories. The first category, included uncompacted and loose ground such as turf, grass, and loose soil. The second category encompassed normal uncompacted ground found in forest floors and pasture fields. In terms of trees, the height considered was 2.5 meters, and conifer trees were assumed by default.

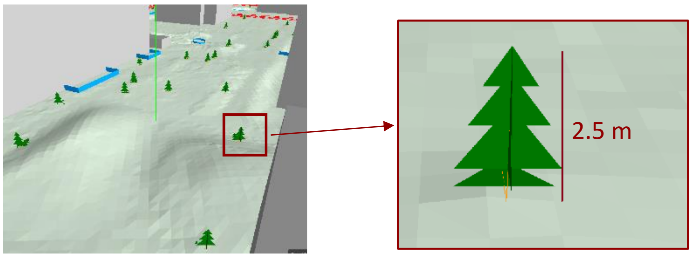


Figure 4.5 - SolitaryVegetationObject layer which was considered as Tree in SoundPLAN

The following sections describe the other parameters that were imported and their corresponding adjustments.

4.6 Processing

Regarding Figure 4.1, the input layers used in SoundPLAN are DEM in ASCII format, roads, buildings, roofs, traffic area, auxiliary traffic area, city furniture, plant covers, and trees in ESRI shapefile format. In order to implement Nord2000 model, certain adjustments and modifications were necessary.

The computer used for the experiments in this thesis was a Windows 10 system with an Intel(R) Core(TM) i9-10940X CPU running at a clock speed of 3.30GHz, with 3.31 GHz turbo boost capability. The system was equipped with 128 GB of installed RAM.

Six procedure executed on the computer took approximately 8 hours to complete. Additionally, 7 days of computation time was required for the final procedure to consider roof configurations for desired building. The powerful computing capabilities of the system allowed for these time-intensive procedures to be completed in a reasonable timeframe.

4.6.1 Parameters for Nord2000

Meteorology: As mentioned in section 2.4, meteorological information was necessary to be defined in the Nord2000 model. Specific weather condition, “moderate worst case - nord2000” is selected (Kragh et al., 2006). The moderate worst case is defined as the meteorological condition with the lowest wind speed and the highest atmospheric stability for a given area. This condition represents a realistic but not worst-case scenario, where sound propagation can be affected by factors such as ground effects and reflections from buildings (Bendtsen, 1999).

Temperature: The study area has an annual mean temperature of 8 °C, which is consistent with the temperature in the southern region of Sweden as reported by SMHI [10].

Type of road surface: In Nord2000, it is essential to consider the specification of the road surface, section 2.4.2. The road surface type is defined using a classification system that includes various types such as Dense Asphaltic Concrete (DAC) and Stone Mastic Asphalt (SMA). DAC is a type of asphalt pavement that is composed of a high percentage of coarse aggregate and provides good durability and skid resistance. SMA is a type of asphalt pavement that is composed of a high percentage of fine aggregate and provides good resistance to deformation and cracking. In the present study, SMA 8 was chosen as it meets the requirements for the road surface conditions in the defined study area. SMA 8 is characterized by a maximum aggregate size of 8 mm, and the roads are at an age of more than 2 years, but not at the end of their life span. In addition, the probability of wet surface conditions is specified as 0%.

Heavy vehicles: The available road data provide the number of heavy vehicles (Swedish: Tunga fordon), but the categories of these vehicles (2 or 3) were not known. In cases where information on the number of light and heavy vehicles is available but not their distribution between categories 2 and 3, an alternative template was developed for the distribution of heavy traffic (A Gustafson & A Genell, 2021). The suggested distribution is 40% for category 2 and 60% for category 3. Additionally, Table 2.1 (for Sweden) is utilized to determine the duration of day, evening, and night for the calculation of L_{den}.

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[10] https://www.smhi.se/data/meteorologi/temperatur/normal-arsmedeltemperatur-1.3973

4.6.2 Method of distribution of receivers

Figure 4.6 demonstrates the 3D representation of receivers at different heights and locations, including various floors of a building. Despite this, the present study focused on generating a Façade Noise Map based on the EU directive guidelines and Nord2000 instruction. This implies that a single receiver situated at a specified height of 4 m above the ground is computed, rather than computing receivers for each individual floor (Figure 4.7). Moreover, in this study, the receivers were placed at a distance of 0.1 m in front of the façade.

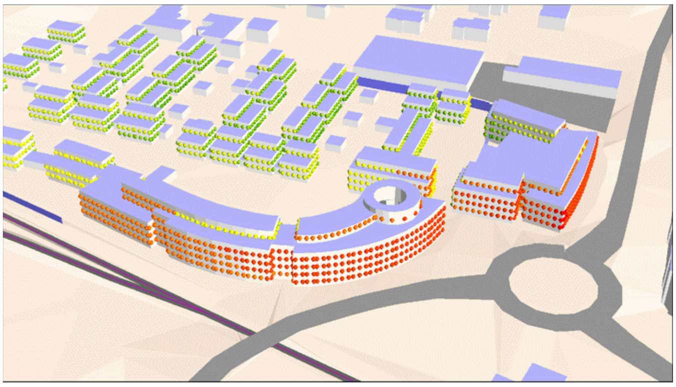

Figure 4.6 - 3D building model showing that it is possible to define noise receivers on different floors of the building using a 3D noise model (SoundPLAN, 2020).

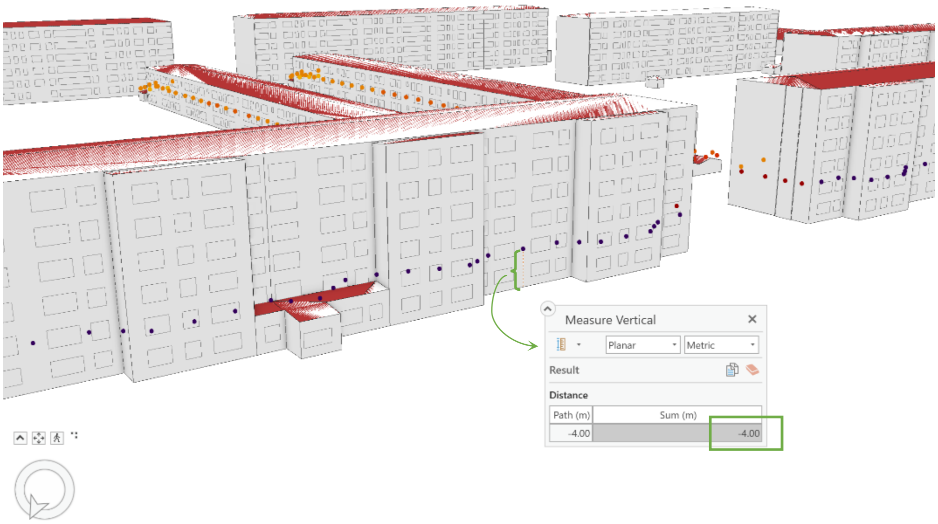

Figure 4.7- receivers is located 4 m above ground (created in ArcGIS Pro)

Horizontally, receivers with spacing according to CNOSSOS-EU was considered in simulation, Figure 4.8.

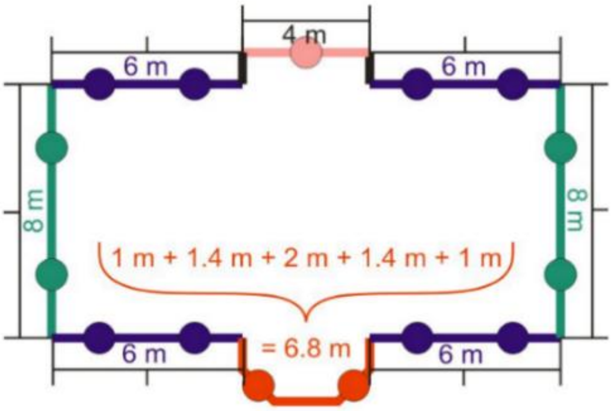

Figure 4.8 - receivers with spacing according to CNOSSOS-EU (Kephalopoulos et al., 2012)

This methodology has been proposed based on the German regulation VBEB[11] (Kephalopoulos et al., 2012). Façades longer that 5 meters are divided into smaller segments for which a single receiver is calculated (green and purple). Façades with a length between 2.5 meters and 5 m are represented by a single receiver (pink). Smaller façades are ignored except if multiple subsequent façade segments reach the combined length of more than 5 meters. In this case the combined façade is then treated as a façade longer than 5 meters and if needed subdivided into 5-meter sections (red).

The additional receivers 2 m in front of the façade according to END are not considered in simulation. This is because it would double the number of receivers and require more processing time.

4.6.3 Determining the sensitivity of simulation to different type of façade

Calculating the exact reflection coefficient for each building façade material is a challenging task since buildings are commonly constructed using a combination of materials. In this study, Table 4.1 based on Nord2000 regulations was used to simulate the reflection loss on different type of façade. These values were defined in both scenarios.

Table 4.1 - reflection properties as single values

Façade type	Reflection loss in dB	Absorption coefficient α	Reflection coefficient
Fully reflective surface	0	0.000	1.000
Hard reflective (concrete, glass)	1	0.206	0.794
Soft reflective (e.g., greenery façade *)	4	0.602	0.398

* Greenery façades are generally considered to be soft surfaces. This is because the vegetation on the façade tends to absorb and scatter sound waves, rather than reflect them back as it occurs on a hard and smooth surface. However, the exact reflection loss value of a greenery façade will depend on several factors such as the density and type of vegetation, the thickness of the vegetation layer, and the distance between the sound source and the façade.

4.6.4 Method of considering roof

One of the challenges encountered when using SoundPLAN for noise simulation is the limitation in representing the actual building structures in the model. This limitation is caused

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[11] Vorläufige Berechnungsmethode zur Ermittlung der Belastetenzahlen durch Umgebungslärm

by the fact that buildings are converted to LOD 1 in SoundPLAN, where the roof layer is not considered in the simulation (section 3.4). In this study, an approach is presented to overcome this limitation by importing 3D roofs as noise protection walls in SoundPLAN. To incorporate the 3D roofs as walls in SoundPLAN, the roofs were extracted from 3CIM. The walls were then positioned “wall floats above ground” to represent the roof layer. Due to time constraints, the noise simulation was implemented for only one building with reflection loss of 0 dB, which is shown with yellow rectangle in scenario 1, Figure 4.3.

The 3D wireframe map (Figure 4.9) is used to depict the buildings and their structures. The blue lines represent the building structure, which likely includes walls, columns, and other support elements. The green lines show the roofs as noise protection walls, which is expected as these roofs provided acoustic insulation. The wireframe map provides a clear view of the overall shape and structure of the buildings. It makes it possible to see how the different parts of the buildings fit together, how they relate to each other in three-dimensional space and evaluate the structural integrity of buildings.

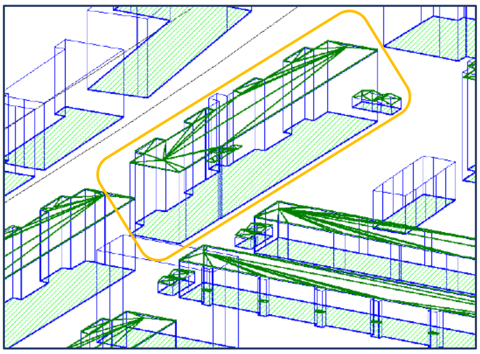


Figure 4.9 - 3D wire frame map from the desired building (created in SoundPLAN).

It should be noted that noise protection wall cannot have receivers. It means that it is not possible to assign receivers to roofs in our study. Figure 4.10 shows that the slope of the roof in the desired building.

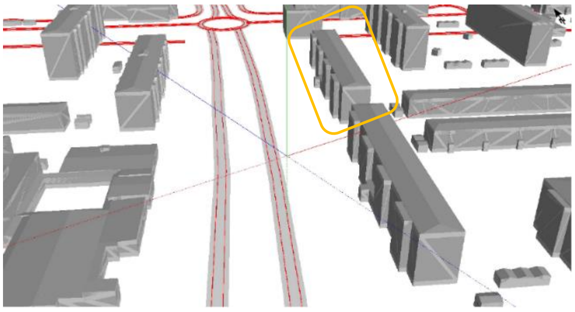


Figure 4.10 - 3D view of desired building that shows the slop of the roof. The figure also illustrates the details of the building’s façade in LOD 2 level (created in SoundPLAN).

5 Result

After importing the 3CIM data and DEM into SoundPLAN, two scenarios were implemented. Scenario 1 analysed the impact of densification by examining an area with both current and planned buildings. Scenario 2 only involved the current buildings in the area. Another procedure was about considering roof to be able to investigate the changes of L_{den}.

Three different reflection losses (0, 1, and 4 dB) were applied to inquire the impact of the façade on noise simulation. According to the Nord2000 regulation, the number of times a sound wave is reflected on a building's façade, also known as the number of reflections, was set at 3, in SoundPLAN.

5.1 Façade Noise Simulation of Nord2000

The results of the noise simulation are displayed in Figure 5.1. It shows six façade noise maps that illustrate the impact of the different reflection losses in both scenarios. In scenario 1 the number of receivers was 617 and in scenario 2, 482. The images at the top of the Figure 5.1 depict the positioning of buildings in relation to the roads.

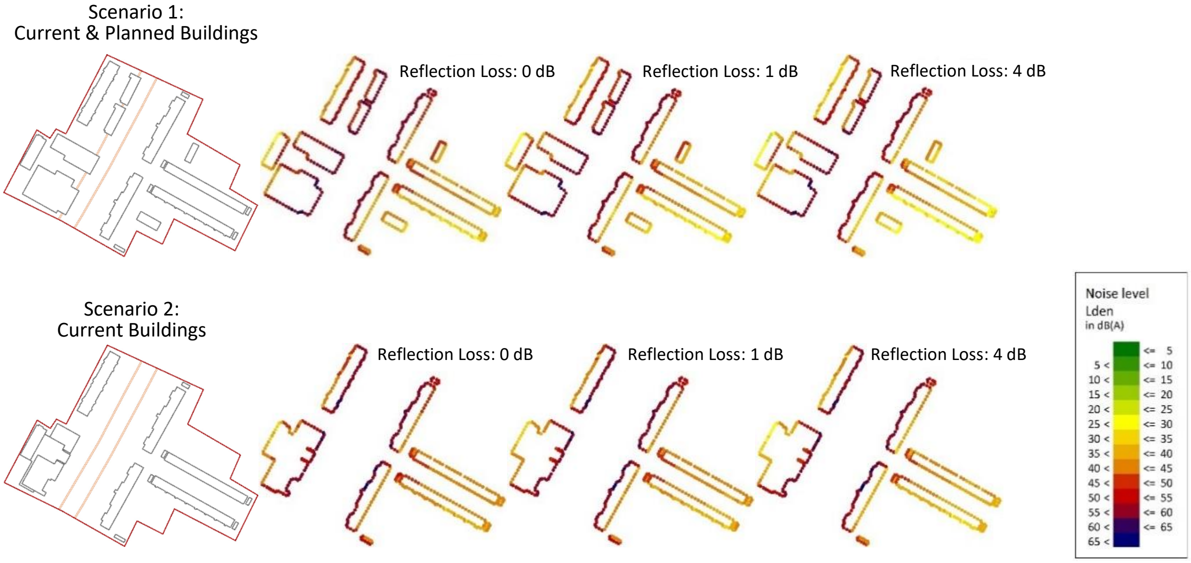


Figure 5.1 - noise level L_{den} (dB), the result of noise simulation for six different procedures

It should be noted that to obtain this result, the data of the entire study area (Figure 4.2) is included in the simulation. This means that if the simulation was conducted for the entire study area, the same simulation result would be obtained for selected buildings.

5.2 Comparison of Noise Simulation Values

This section presents a comparison between six outcomes derived from the implementation of the Nord2000 model. An overview of the obtained results, such as the minimum and maximum values, as well as the mean value and standard deviation of each of the simulated procedures, are shown in the Table 5.1. In the first scenario, which aimed to investigate the densification effect, some buildings were planned. When comparing the minimum, maximum, and mean values of this scenario to those of scenario 2, it was observed that they were lower. This is due to the fact that the planned buildings have a great capacity to reduce noise through reflection. The standard deviation values in scenario 1 are greater than in scenario 2, which suggests that the data points in scenario 1 are more spread out or varied compared to scenario 2. In other words, there is obviously more variability in the data in scenario 1 than in scenario 2.

Table 5.1 overview of the obtained results of L_{den} for six procedures

	Minimum	**Maximum**	**Mean**	**Standard deviation**
Scenario 1 (617 receivers)				
Current+Planned Building (RL: 0 dB)	27.9	64.0	46.8	8.66
Current+Planned Building (RL: 1 dB)	25.9	62.9	45.5	9.06
Current+Planned Building (RL: 4 dB)	21.4	61.2	42.9	10.11
Scenario 2 (482 receivers)				
Current Building (RL: 0 dB)	32.2	80.4	48.5	7.74
Current Building (RL: 1 dB)	30.5	80.4	47.6	8.19
Current Building (RL: 4 dB)	26.6	80.4	45.7	9.24

Two different scenarios were examined to investigate the impact of various façade types, building density in urban area and building's orientation on noise levels. The results of scenario 1 are presented in Figure 5.2 and Table 5.2, where the values of L_{den} and specific mean values of L_{den} in various building conditions are reported. The regions in Figure 5.2 are defined as the following,

1A: The façades of the building towards the road with the most exposure of traffic noise are within the pink rectangles.

1B: The façades of the building behind the main building towards the road are within the green rectangles.

1C: The façades of the building is parallel to the road but not directly, are within the blue rectangle.

1D, 1E: The façades of the buildings are vertical to the road, are within the blue rectangle.

The findings indicate that the L_{den} values in region 1B are consistently lower than those in region 1A, with differences of 11.9 dB, 12.9 dB, and 15.6 dB for 0 dB, 1 dB, and 4 dB, respectively. This suggests that not only the position of the building relative to the road but also the soft façade with reflection loss 4 dB significantly affect the L_{den} levels at the rear of the building. Additionally, the L_{den} values for regions 1D and 1E are consistently lower than those for parallel building C, with Building 1C showing higher values of L_{den} (47.5 dB, 46.2 dB, and 43.2 dB for 0 dB, 1 dB, and 4 dB, respectively) compared to Building 1D (41.3 dB, 39.9 dB, and 37.1 dB for 0 dB, 1 dB, and 4 dB, respectively) and Building 1E (37.9 dB, 36.4 dB, and 33.1 dB for 0 dB, 1 dB, and 4 dB, respectively). This highlights the significant role of building orientation in L_{den} levels.

In scenario 2, presented in Figure 5.3 and Table 5.3, the values of L_{den} and specific mean values of L_{den} in various building conditions are reported. The regions in Figure 5.3 are defined as the following,

2A: The façades of the building towards the road with the most exposure of traffic noise are within the pink rectangles.

2B: The façades of the building behind the main building towards the road are within the green rectangles.

2D, 2E: The façades of the buildings are vertical to the road, are within the blue rectangle.

The differences between region 2A and 2B in scenario 2 are 14.1 dB, 14.3 dB, and 16.7 dB for 0 dB, 1 dB, and 4 dB, respectively. Furthermore, the noise level values in scenario 2 for buildings 2D and 2E are higher than those in scenario 1, indicating that the Planned buildings was able to reduce the noise levels in these buildings by an average of 3.7 dB.

Regarding the comparison between scenarios 1 and 2, the results reveal that the density was able to reduce the noise levels in the rear of the building in a fully reflective surface (RL: 0 dB) by 2.2 dB, the hard-reflective surface (RL: 1 dB) by 1.4 dB, and the soft reflective surface (RL: 4 dB) by 1.1 dB. Furthermore, there was almost no change in the noise levels in the front of the building facing the road with different reflection losses.

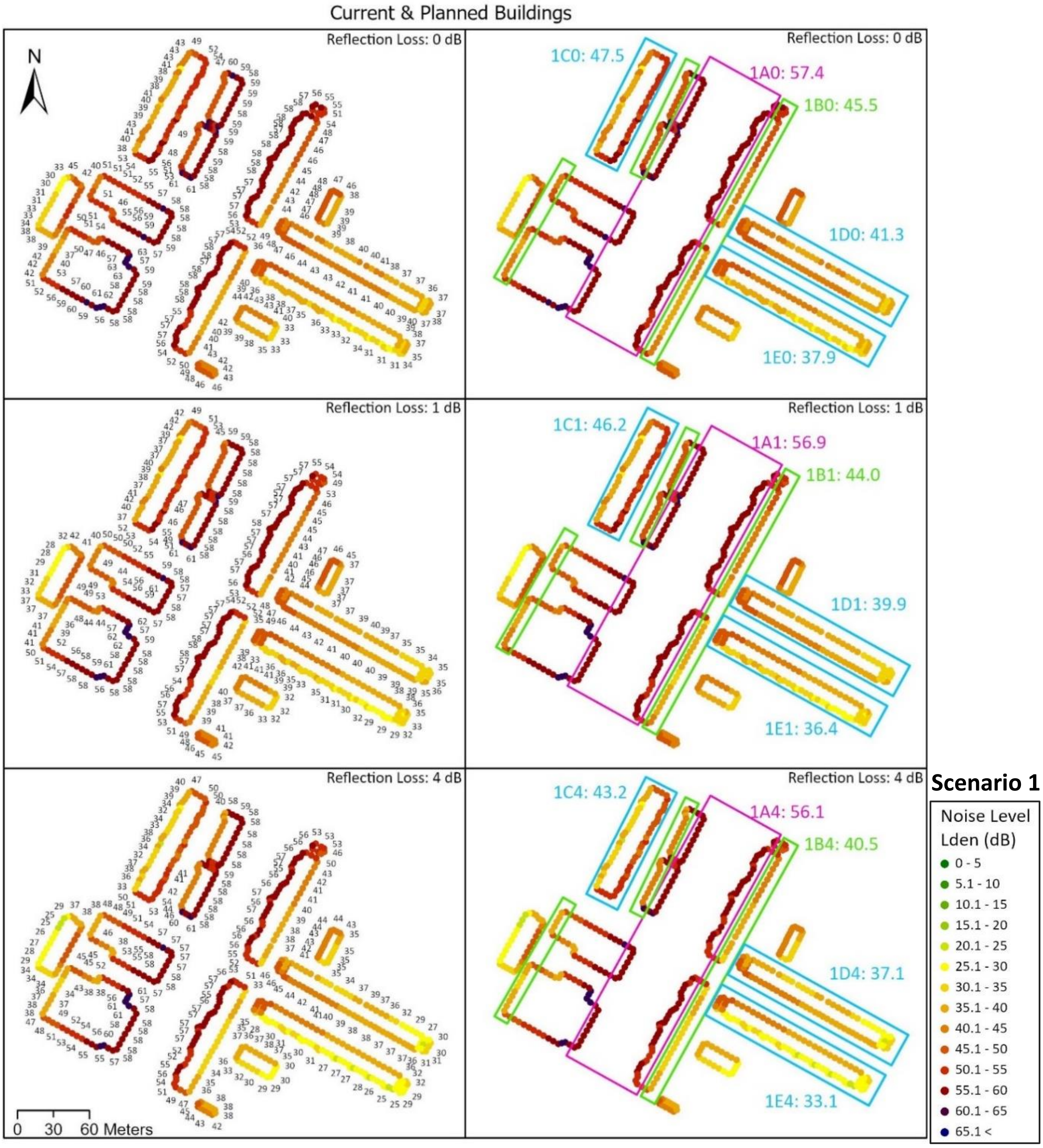


Figure 5.2 - comparison of L_{den} obtained from noise simulation, scenario 1. The code inside the map is as follows: Scenario 1 + position of buildings + reflection loss value. The text string "1A0:57.4" means scenario one, for the area A (façade of the building facing the road) with reflection loss 0 dB; the simulated value 57.4 dB.

Table 5.2 - the mean values of L_{den} (dB) in different situation of buildings in scenario 1.

Scenario 1		0 dB	1 dB	4 dB
Front of Building*	**A**	57.4	56.9	56.1
Rear of Building **	**B**	45.5	44.0	40.5
Parallel Building	**C**	47.5	46.2	43.2
Vertical Building	**D**	41.3	39.9	37.1
Vertical Building	**E**	37.9	36.4	33.1

* All stated positions of the buildings are relative to the road (Figure 4.3).

** The rears of buildings are contained within the three green rectangles all green rectangles.

Figure 5.3 - comparison of L_{den} obtained from noise simulation, scenario 2. The code inside the map is as follows: Scenario 2 + position of buildings + reflection loss value. The text string "2A0:58.0" means scenario two, for the area A (façade of the building facing the road) with reflection loss 0 dB; the simulated value 58.0 dB.

Table 5.3 - the mean values of L_{den} (dB) in different situation of buildings in scenario 2.

Scenario 2		0 dB	1 dB	4 dB
Front of Building*	**A**	58.0	56.9	56.1
Rear of Building **	**B**	43.9	42.6	39.4
Parallel Building	**C**	-	-	-
Vertical Building	**D**	43.9	42.9	40.7
Vertical Building	**E**	41.7	40.5	38.0

* All stated positions of the buildings are relative to the road (Figure 4.3).

** The rears of buildings are contained within the three green rectangles all green rectangles.

5.3 Noise Simulation Considering Roof Configuration

The results of the noise simulation considering roof configuration in SoundPLAN is provided in Figure 5.4. The number of receivers were 61. It should be noted that to obtain this result, the data of the entire study area (Figure 4.2) is included in the simulation. This means that if the simulation was conducted for the entire study area with roofs configuration, the same simulation result would be obtained as it was implemented for a single building.

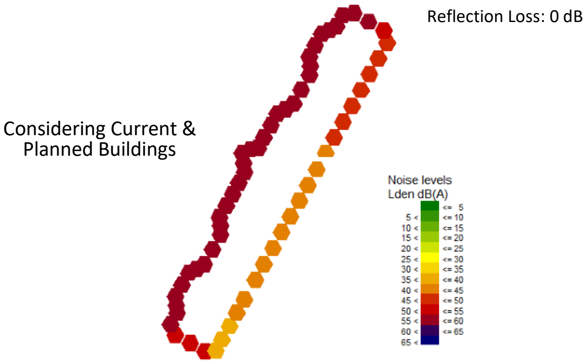


Figure 5.4 - the result from SoundPLAN that shows the L_{den} values for one building considering roofs configurations.

This noise simulation Nord2000 model was applied for current and planned building and reflection loss 0 dB. An overview of the obtained results, such as the minimum and maximum value, as well as the mean value and standard deviation of the simulated procedure, is shown in the Table 5.4.

Table 5.4 - overview of the obtained results of L_{den} for the last procedure considering rood.

	Minimum	**Maximum**	**Mean**	**Standard deviation**
Roof (61 receivers)				
Current+Planned Building (RL: 0 dB)	36.2	58.0	52.1	6.83

The Figure 5.5 shows the situation of building in simulated area and 3D scene of building. Figure 5.6 illustrates the same building which is obtained from scenario 1 with reflection loss 0 dB and flat roof (on the left side of the figure) in comparison of the other procedure considering roof configuration (on right side of the figure).

The mean value of the building without roof is 52.3 dB and the building with roof is 52.1 dB. It means that roof, in this simulation, can reduce noise level mean 0.2 dB. The mean value for front of the building is 0.1 dB and for rear of the building 0.6 dB.

It can be said that roofs did not play significant role in noise simulation in this case. Since it needs more time for executing procedures with roof in Nord2000, ignoring the roof layer can be a good suggestion.

Figure 5.5 - L_{den} obtained from noise simulation in dB.

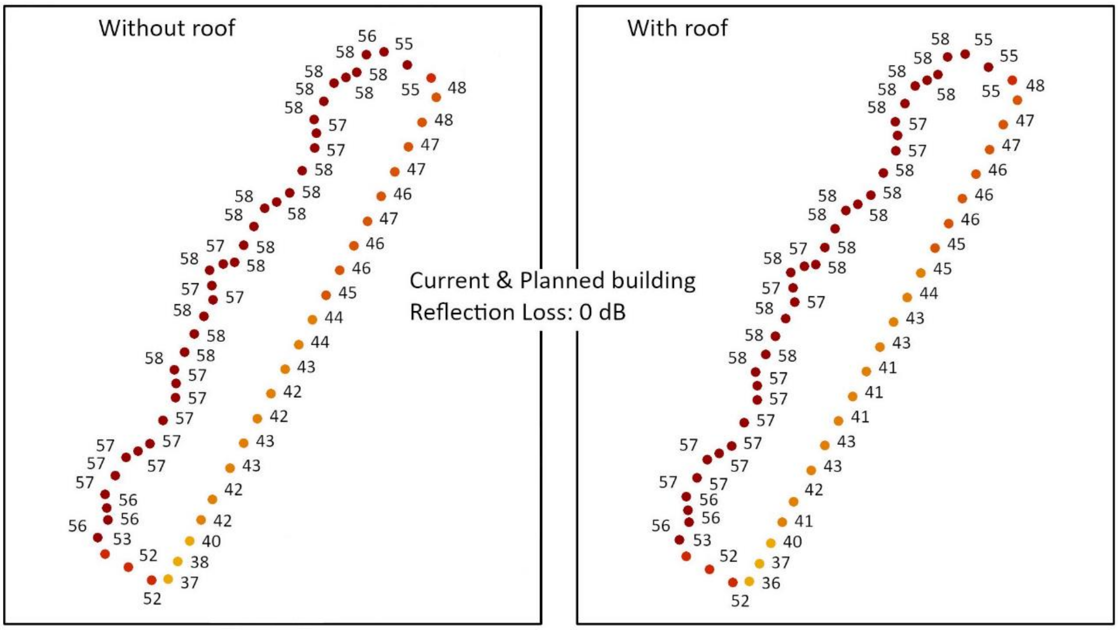


Figure 5.6 - comparison of two noise simulations in the same situation but the left image is without considering roof and the right image is with considering roof.

6 Discussion

The aim of this study was to investigate the effects of changes in acoustic properties on noise simulation output in case study urban areas using 3D city models (3CIM) as input. The study focused on pre-processing and adapting the 3CIM model according to Nord2000 requirements as implemented in the noise modelling tool SoundPLAN. The study considered buildings and barrier objects such as, traffic auxiliary, city furniture, and vegetation (e.g., plant cover, trees). The road traffic acted as sources of noise and the receivers were placed on building façades. Two simulation scenarios were compared to investigate the impact of densification, and the effect of noise reflection on three types of assumed building façades was examined. Additionally, the effect of roofs on noise levels was investigated.

The first research question focused on identifying the input geospatial data requirements for the Nord2000 model. The results showed that the Nord2000 model requires more detailed input data compared to other models, resulting in higher demands on computer resources and computation time. Therefore, the applicability of Nord2000 is limited to smaller geographical areas, and its use may not be feasible for large-scale studies.

The second research question aimed to investigate how changes in acoustic properties for different building façade types affect simulated noise values. The results indicated that the acoustic properties of the building façade can affect noise levels (L_{den}). The simulation results showed that soft façades compared to a hard surface can affect the dispersion of noise and thus reducing the noise level. As a result, the analysis of the noise maps revealed that the noise levels decreased as the reflection loss increased. Moreover, the results indicated that the location of the noise source and the orientation of the building (in relation to the main noise source) also influenced the noise levels.

The third research question investigated the effect of roofs on noise levels. The simulation results showed that sloping roofs had not so much impact on noise levels compared to flat roofs. In this study, green roof (soft roof) was not investigated. Green roofs have the potential of reducing noise levels further. However, this topic needs to be further investigated in future studies to obtain a more comprehensive understanding on the effect of roof types and roof materials in noise propagation.

6.1 Limitations

There are several limitations to this study that should be acknowledged. Firstly, the study did not have observed noise values to compare with the simulated results, which makes it challenging to verify the accuracy of the noise prediction models. Secondly, the use of Nord2000 may not be feasible for large-scale studies due to its high demand for computer resources and computation time. Lastly, this study utilized a specific 3D city model (3CIM in Malmö), a specific noise propagation model (Nord2000) and a specific software (SoundPLAN). It is important to acknowledge that there are geospatial data sources, other noise propagation models and software options available for noise simulation. As such, it is possible that the use of different models and software may have led to different results in this study.

Moreover, 3CIM does not provide information about façade material. Instead, the study used reflection loss according Nord2000 recommended values to account for the effect of different façade types on noise levels when the real values are not provided. This approach may have limitations since the reflection loss values used may not precisely reflect the acoustic properties of the actual materials used in the building façades. Therefore, the results of the study should be interpreted with caution and further research is needed to investigate the impact of façade material on noise levels in urban areas.

6.2 Effects of façade material

The results obtained from the noise simulation indicate that the different types of façades exhibit a notable influence on the acoustic performance of the building's rear (in relation to main noise source). It can be inferred that the façade facing the front of the building effectively attenuates the reflected sound waves, thereby preventing their propagation towards the rear of the building.

Building density in urban areas and their orientation, as well as façade reflection losses, affect noise levels in simulated areas. Findings can be separated into two parts: the rear and front of the building and the vertical and horizontal buildings.

Part 1: in both scenarios, the results showed that there was almost no change in the noise levels in the front of the building facing the road (region A). Scenario 1, the difference of L_{den} in region A between RL 0 dB and 1 dB is 0.5 dB and L_{den} between RL 1 dB and 4 dB is 0.8 dB. Scenario 2, the difference of L_{den} in region A between RL 0 dB and 1 dB is 1.1 dB and L_{den} between RL 1 dB and 4 dB is 0.8 dB. This suggests that other strategies, such as noise barriers, may reduce noise pollution in these areas more effectively.

In addition, at the rear of building (region 1B and 2B), the L_{den} values are consistently lower than those at the front of building, region A. This reduction of noise was increased from fully reflective to soft façade in both scenarios, Table 6.1. The results suggest that the implementation of a soft façade can enhance noise absorption at the front of the building, and subsequently reduce the noise levels that propagate towards the rear of the building after reflection.

Table 6.1 - the differences between the front and rear of buildings in both scenarios. The values are in dB.

Subtracting of region, A from B	0 dB	1 dB	4 dB
1A - 1B	11.9	12.9	15.6
2A - 2B	14.1	14.3	16.7

The comparison between scenarios 1 and 2 showed that density was able to reduce the noise levels (L_{den}) in the rear of the building in a fully reflective surface (RL: 0 dB) by 2.2 dB, the hard-reflective surface (RL: 1 dB) by 1.4 dB, and the soft reflective surface (RL: 4 dB) by 1.1 dB.

Part 2: On the other hand, the L_{den} values for regions 1D and 1E are consistently lower than those for region 1C, highlighting the significant role of building orientation in L_{den} levels. However, building density (according to scenario 1) was able to reduce the noise levels in buildings 2D and 2E by an average of 3.7 dB, see Table 5.2 and Table 5.3. This indicates the potential of densification as a noise reduction strategy. However, it should be noted that the results are in the constant noise source condition in both scenarios.

The study suggests that urban planning and design should consider factors such as building density, orientation, and façade reflection losses in order to meet noise reduction standards set by the WHO. This has important implications for creating healthier and more liveable urban environments. However, the study also highlights that the effectiveness of these considerations may vary depending on the location, and other noise-reducing strategies such as noise barriers may be more effective in some areas. This suggests that a combination of different strategies may be necessary to effectively reduce traffic noise pollution in the urban environments. Additionally, it is important to note that noise pollution is just one of the many factors that need to be considered in urban planning and design, and therefore, a comprehensive approach is needed to create sustainable and liveable urban environments.

6.3 Effects of roof

The approach presented in this study provides a solution to the limitation in representing the roof layer in SoundPLAN. The use of 3D roofs as noise protection walls improves the accuracy of the noise simulation by considering the actual building structures. However, the approach has some limitations such as the need for a 3D model of the building's roof semantically which 3CIM provided. Also, by considering 3D roofs layer in the simulation, it increased the time required for the simulation significantly. Because of computational time limitations, the simulation was implemented for 61 receivers and for one procedure from scenario 1, RL 0 dB. Further research is needed to investigate the impact of using different reflection loss values and to assess the validity of the approach in larger scale noise modelling scenarios. It is worth investigating whether other models than Nord2000 exist that can execute the same simulation in shorter time. Although the approach did not show a significant change in the amount of noise level compared to the case where the roof was assumed to be flat, it has the potential to improve the accuracy of noise simulations by considering actual building structures, which could be useful further studies.

6.4 Use of GIS for Interpretation of Noise Simulation Results

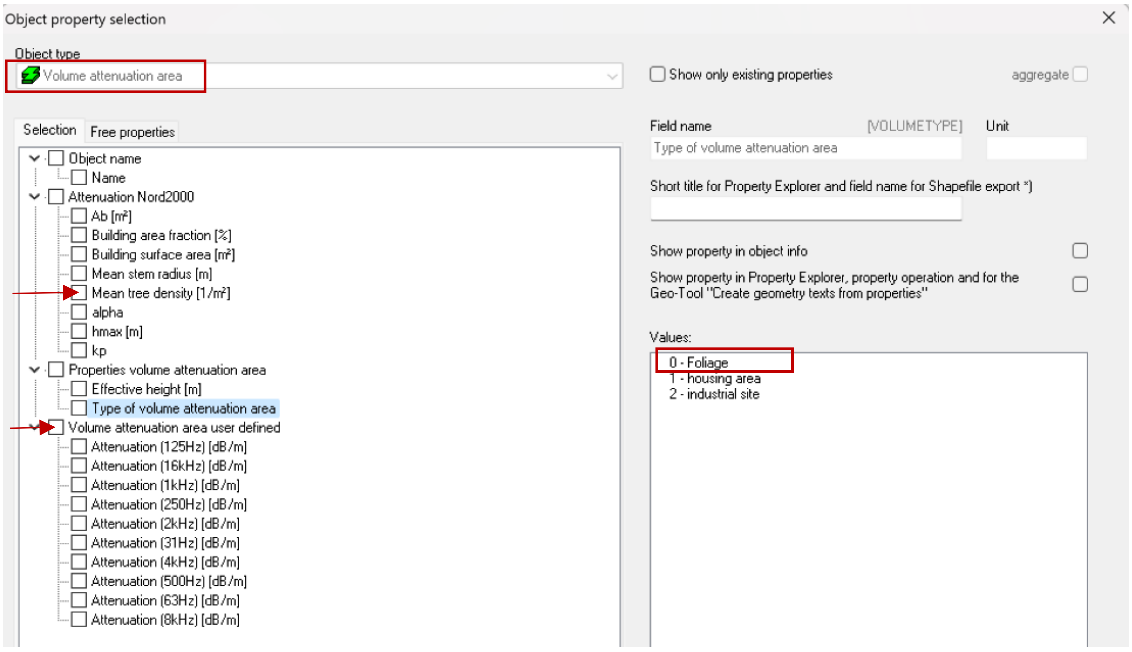
This study utilized ArcGIS Pro as a tool for interpreting the noise simulation results obtained through SoundPLAN. As discussed in Chapter 1, GIS can provide a visual representation of data, and in this case, it allowed for a better representation of the noise map. Additionally, the use of GIS facilitated the preparation of average noise values in different parts of the buildings. This approach improved the effectiveness of the noise simulation results and demonstrates the utility of GIS as a complementary tool for presenting noise modelling results.

6.5 Future work

In this study, the outdoor noise in SoundPLAN was calculated using LOD 1 buildings, which constituted a limitation. To solve this issue, the roofs of the buildings were considered as a noise protection wall that was floating on top of the building. While it may be possible to also consider windows as a noise protection wall. However, there are limitations to be considered, such as the capacity of SoundPLAN and the constraints of data availability in 3D city models (e.g., the 3CIM specifications, Uggla et al., 2023).

Further research is recommended to explore this topic in greater depth. Specifically, it would be valuable to investigate the impact of using different reflection loss values and assess the validity of the approach in larger-scale noise modelling scenarios. Additionally, exploring alternative simulation models that require less time for simulation may be beneficial. By conducting additional research, a more comprehensive understanding of the effectiveness of different noise reduction strategies can be gained, leading to the development of more effective urban planning and design solutions for reducing noise pollution in urban environments.

Finally, the inclusion of tree layers in the study noise simulations was limited to importing conifer trees with a constant height of 2.5 meters. The current study did not extensively examine the effects of tree foliage on noise reduction. However, SoundPLAN provides an option to represent tree foliage as *Volume Attenuation Areas*, considering the foliage's characteristics (Figure 6.1). This feature enables the precise definition of tree volumes and the assessment of reflection loss associated with each tree separately. As a suggestion for further investigation, it is recommended to explore this aspect in subsequent research endeavours.



Object type: Volume attenuation area

Field name: Type of volume attenuation area [VOLUMETYPE]

Unit:

Values:
0 - Foliage
1 - housing area
2 - industrial site

Figure 6.1 - Volume Attenuation Areas Object which indicates its characteristics.

7 Conclusions

This study aimed to investigate “the requirements of data for Nord2000 model”, “the impact of different façade types”, “building density”, and “roof configuration” on noise levels using SoundPLAN software. Two scenarios were examined, scenario 1 which involved current and planned buildings, and scenario 2 which only considered current buildings. The noise maps obtained through simulations revealed that the reflection loss and the orientation of the buildings notably influenced the noise levels. Moreover, the results showed that the approach of densification in urban areas was able to reduce the noise levels in the rear of the building but had almost no effect on the noise levels in the front of the building facing the road. It should be noted here that this reduction is under the assumption that the noise source (road traffic) is constant. In a real-world scenario, the road traffic might increase due to that more people are living in the area.

Furthermore, the simulation considering roof configuration showed that the mean value of the building with roof was slightly lower than that of the building without a roof, indicating that the roof can reduce the noise level mean by 0.2 dB.

Overall, the findings of this study provide valuable insights into the impact of building density, orientation, and roof configuration on noise levels. The results can be useful for urban planners and policymakers to make informed decisions regarding building design and urban planning to reduce noise pollution in urban areas. Moreover, it addresses the issue of what data is required in 3D city models to perform noise simulations; specifically, it highlights the need to include in information about façade material in 3D city models, which is currently not supported by the 3CIM specifications. Further studies can be conducted to investigate the impact of other factors such as considering windows, exploring less time simulation models, and effect of tree foliage to obtain noise levels.

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Appendix I Octave band

Table I.1- Each Octave Band consists of range of frequencies. The centre frequency is the representative of other frequencies in a range.

Lower Band Limit [Hz]	Centre Frequency [Hz]	Upper Band Limit [Hz]
44	63	88
88	125	177
177	250	355
355	500	710
710	1000	1420
1420	2000	2840
2840	4000	5680
5680	8000	11,360

Table I.2 - Each One-Third Octave Band consists of range of frequencies. The centre frequency is the representative of other frequencies in a range.

Lower Band Limit [Hz]	Centre Frequency [Hz]	Upper Band Limit [Hz]
44.7	50	56.2
56.2	63	70.8
70.8	80	89.1
89.1	100	112
112	125	141
141	160	178
178	200	224
224	250	282
282	315	355
355	400	447
447	500	562
562	630	708
708	800	891
891	1000	1122
1122	1250	1413
1413	1600	1778
1778	2000	2239
2239	2500	2818
2818	3150	3548
3548	4000	4467
4467	5000	5623
5623	6300	7079
7079	8000	8913
8913	10,000	11,220
11,220	12,500	14,130
14,130	16,000	17,780
17,780	20,000	22,390

Appendix II Sound pressure

Table II.1 - relationship between Sound Pressure Level and sound pressure according to Equation 2.5.

SPL [dB]	Sound Pressure [Pa]	Typical sound source
200	2×10^{5}	Jet engine at take-off (atmospheric pressure)
190	6.3×10^{4}	
180	2×10^{4}	
170	6.3×10^{3}	
160	2×10^{3}	Ram jet
150	6.3×10^{2}	
140	2×10^{2}	Propeller engine 30 m overhead
130	63	
120	20	Pain threshold
110	6.3	
100	2	Heavy lorry at kerbside
90	6.3×10^{-1}	Heavy traffic at kerbside
80	2×10^{-1}	Noisy office
70	6.3×10^{-2}	
60	2×10^{-2}	Normal conversation at 1 m
50	6.3×10^{-3}	Average office
40	2×10^{-3}	Quiet house
30	6.3×10^{-4}	Recording studio
20	2×10^{-4}	Gently rustling leaves
10	6.3×10^{-5}	
0	2×10^{-5}	Threshold of hearing

Appendix III Ground type in Nord2000

Table III.1 - classification of ground type in Nord2000

Impedance class	Representative flow resistivity σ [kPas/m2]	Description
A	12.5	Very soft (snow or moss-like)
B	31.5	Soft forest floor (short, dense heather-like or thick moss)
C	80	Uncompacted, loose ground (turf, grass, loose soil)
D	200	Normal uncompacted ground (forest floors, pasture field)
E	500	Compacted field and gravel (compacted lawns, park area)
F	2,000	Compacted dense ground (gravel road, parking lot, ISO 10844 asphalt)
G	20,000	Hard surface (most normal asphalt)
H	200,000	Very hard and dense surface (dense asphalt, concrete, water)

The flow resistivity of the ground surface defines the ground surface type. The flow resistivity can be used directly to specify the ground type, or it can be used indirectly by using the classes A to H indicated in Table III.1. User guides of Nord2000 is recommended to employ ground types D and G in simple computations where the only distinction is between "soft" and "hard" ground. In such computations, the road is represented by ground type G.

Appendix IV UML diagram of CityGML Noise ADE

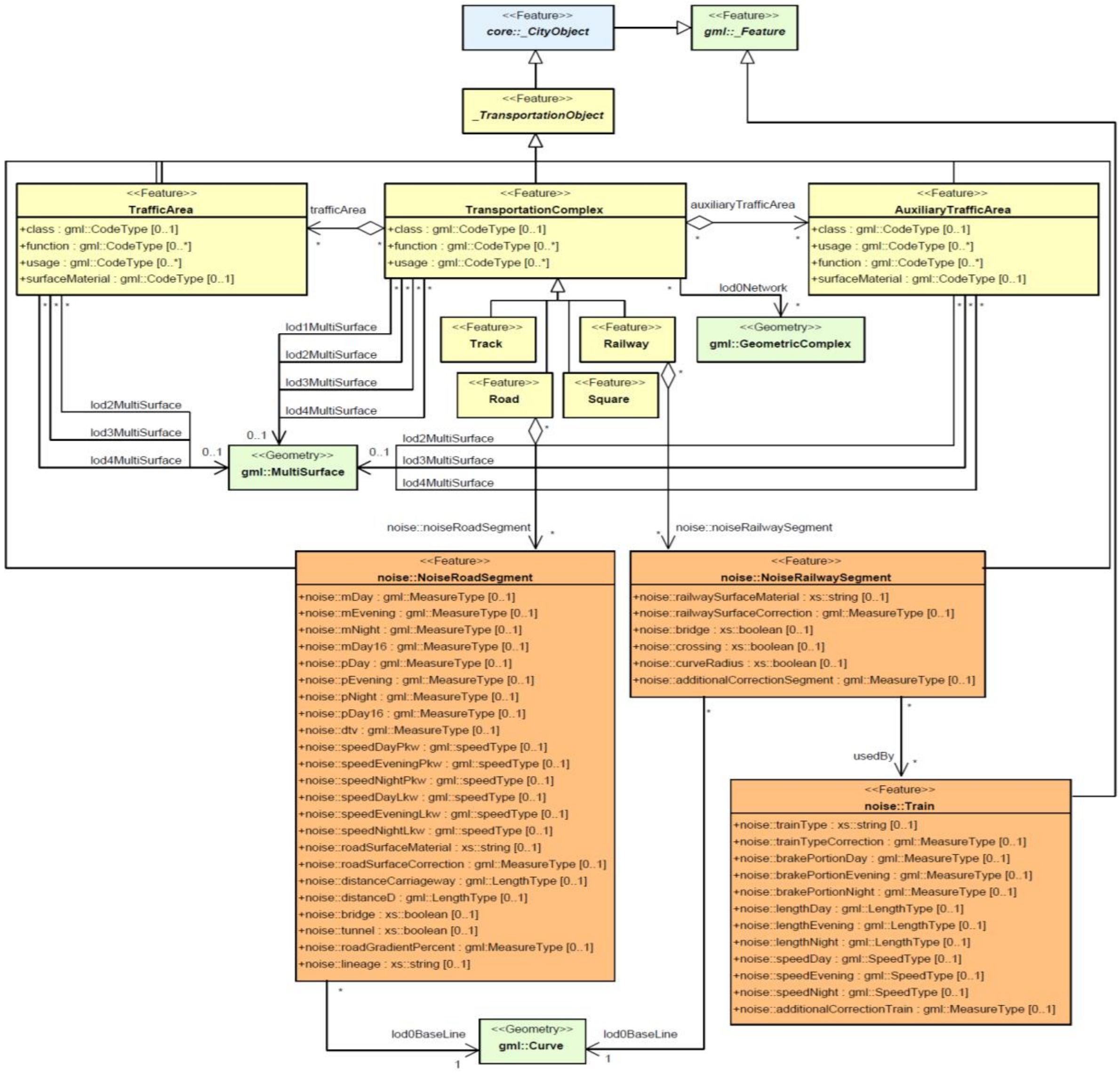

Figure IV.1 - UML diagram of CityGML Noise ADE. Prefixes denote XML namespaces connected with model elements. Elements without a prefix are specified in the CityGML 'Transportation' module (light yellow). The prefix 'noise' is connected to the CityGML Noise ADE (light orange).

Appendix V Schema of transportation theme

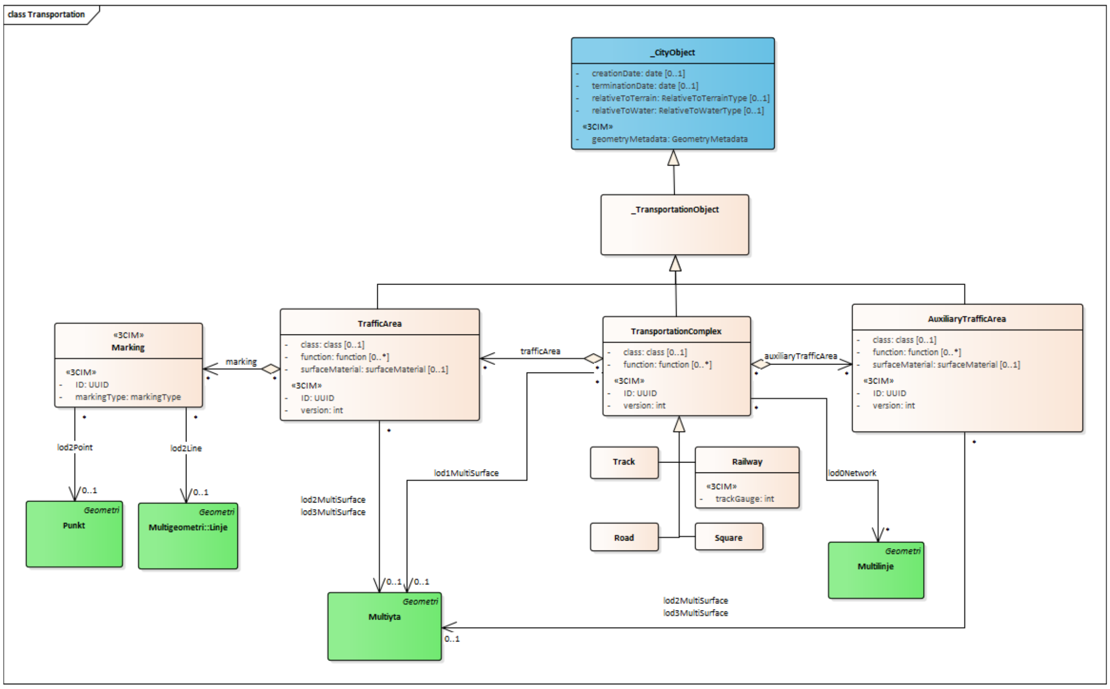

Figure V.1 - schema of transportation theme. The ADE attributes are added to the CityGML classes, under the namespace <<3CIM>>. Additionally, the ADE class "Marking" has been created under the namespace <<3CIM>> to represent information about road markings.

Appendix VI Description of attributes

Table VI.1 - description of parameters based on CNOSSOS-EU

	Attribute	Description
Road object type	**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
Noise protection wall object type	**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
Ground absorption area object type	**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
Tree object type	**Graphic object ID**	Unique ID of a tree
	Tree height	Height of a tree object
Building object type	**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