3D noise mapping in urban areas

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Abstract

Noise mapping is the process of determining and visualising noise impact on the environment in order to support environmental policies. Currently most noise impact studies are based on a 2D approach. The 3D output of noise simulation software is processed and visualised in 2D and combined with 2D topographical and other data, such as population distribution, to quantify the effects. The research described in this paper aims at improving visualisation and quantification of noise impact on the environment by generating a 3D noise map where 3D effects are relevant. Based on the specific demand, an approach is presented to generate a 3D noise map as basis for noise impact studies. The proposed concept is proofed by applying it to a sample noise impact study. From experiences with the sample it can be concluded that the 3D noise map offers significant insight in situations where 3D noise effects are relevant, i.e. in urban areas. Here current 2D noise maps have limitations. In addition more accurate assessment of noise impact is possible in particular when different floors of a building close to the noise source and/or behind noise barriers are considered. This paper also elaborates on accuracy aspects in all phases of noise modeling, including reporting on initial experiments of 3D noise interpolation.

Keywords: 3D noise mapping, spatial modelling, environmental impact studies

1. Introduction

2D GIS has been widely and successfully used in environmental impact studies to show impact of spatial phenomena such as soil pollution, air pollution and noise on the environment. However it can be expected that a 3D approach can offer fundamental improvements when 3D effects are relevant, i.e. in urban areas. The objective of the research presented in this paper is to study how noise impact studies in those situations can be extended towards 3D in order to improve visualisation of noise impact and to increase accuracy of noise impact assessment studies. In rural areas, where considerable noise fall with height up a building is less relevant a 2D representation may still do.
This multi-disciplinary research is executed by the company dBvision (providing knowledge on noise and its impact studies) and ITC (providing expertise on geo-information processing). The aim of the presented research is to show how noise impact studies can be improved using basic 3D GIS functionalities rather than how 3D GIS functionalities can be improved in general. In that respect this research is a typical ‘design’ research as it is recognized in the discipline of information systems. According to Association for Information

Systems (2007) design research should a) show that there is a demand for a design; b) review existing and propose a new design; c) show proof of concept by applying it to sample data; d) show that it can represent concepts that are impossible with existing designs; and, e) show that the improved design can meet more general problems. All these aspects will be addressed in this paper.
In section 2 the case of noise is presented defining the motivation for this research: why is noise a problem; how are noise impact studies currently carried out; what are problems of current 2D approach in noise assessment and management. Section 3 presents a methodology for a 3D approach in noise impact studies by the integration of a surface representation of noise levels at a surface following the height of the terrain (including buildings) with a 3D city model. The results of the 3D noise map, including applying it to a noise impact study, are presented in section 4.
Main aim of noise impact studies, as object of this research, is to visualise and quantify the overall noise impact. Therefore increasing accuracy of calculated noise levels on specific locations is not the objective of this research. However improving accuracy of noise models is an important scientific issue and will therefore be addressed in section 5 against the background of the complete noise modelling process (from data collection and 3D noise interpolation, to use in a specific application). The paper ends with conclusions in section 6.
The cities Paris and Hong Kong already produced 3D noise maps (see Butler, 2004; respectively Wing and Kwong, 2006). Also the MITHRA-tool (CSTB, 2007; Rapin et al, 2002) provides a 3D presentation of noise levels. These 3D noise maps, projecting noise levels on buildings, look promising. The additions of the research presented in this paper is the generation of a noise surface and of 3D contours as well as a generic method for visualisation. The noise surface and 3D contours are both representations of noise levels following the terrain and provide therefore a more detailed presentation of the noise situation than the repsesentation of noise levels on buildings. The generic visualisation is just another representation of the information. Conversions to virtual reality environments are not necessary to visualise the 3D information. As a consequence the noise surface as produced in this research can be used directly to quantify noise impact in 3D as will be seen in this paper.

2 Describing the case of noise

This section presents the case of noise. The noise problem including policies to reduce noise problems are introduced in section 2.1. Section 2.2 describes current practice of noise impact studies. The demand for a 3D approach for noise assessment and management is described in section 2.3.

2.1 Noise problem

Noise pollution in large urban areas, mainly caused by industry and road and railway traffic, is considered as a serious environmental problem (Silvia et al., 2003). For the management of these noise problems many governments require that the environmental impact of noise produced by planned constructions such as infrastructure and industries is assessed before construction starts. If negative effects are expected, measures need to be taken. These measures may comprise a change of the plan, construction of noise barriers, use of quiet road surfaces and insulation of houses.
Besides the prevention of future noise problems, steps are being taken to reduce present noise effects. In order to have a common European mitigation program to control noise levels the European Union has formulated a directive on noise pollution (European Union, 2002). The directive prescribes a common approach for all member countries to prevent and reduce the harmful effect of noise. A major component of this approach is a common method to produce strategic noise maps for all major cities, roads, railways, airports and industrial sites. The strategic noise map presents noise levels caused by existing noise producers. The EU-directive

requires the noise map to represent noise levels at a height of four meters from the surface. The EU-directive further requires publishing the noise maps to the public and updating the maps every five years. Based on these maps, plans need to be made to reduce the impact of noise, also every five years. The EU-directive does not contain common noise limits. These can be determined by each member state.

2.2. Noise impact studies

Noise impact studies consist of two stages: 1) the calculation of noise levels and 2) the combination of other spatial and non spatial data with the calculated noise levels to produce insight into the impact of noise.

Calculation of noise

In noise impact studies, noises levels are determined with computer simulations models rather than with noise measurements. There are several reasons for this. First of all field measurements are time consuming since the noise levels concern the yearly averaged values and can only be done under the appropriate weather conditions. In practice it is difficult to execute an adequate number of measurements in order to produce reasonable noise maps. Furthermore it is impossible to determine future noise levels by measurements whereas noise simulation models can deal with future situations. In addition it is shown that models can predict noise levels within an acceptable level of uncertainty for most situations. Therefore noise calculation methods, which have been validated and calibrated extensively with field measurements, are widely accepted to provide reliable information on noise levels. In computer models that implement the calculation methods, noise levels are calculated on 'virtual microphones' (observation points). A virtual microphone, specified with a x,y,z coordinate, is a point that reports what the noise level would be at a certain location under given circumstances. In the computer models noise levels are computed on 3D data points based on:

1. Information on the noise source (roads in this case): traffic intensity, maximum speed, road surface type, average emission of different vehicle types.
2. Information on aspects that influence noise propagation such as noise obstruction by objects (like buildings, noise barriers) and noise absorption (like open areas with grass or bare soil). This information also covers heights of buildings and of other topography.
3. 3D distance and direction of the data points with respect to the location of the noise source.

Determining the impact of noise

GIS functionalities are commonly used to assess the impact of noise by producing strategic noise maps. Noise maps can be made with the combination of interpolated surface of noise levels and spatial data covering the area of the study. An example of a noise map is shown in figure 1 (Kluijver and Stoter, 2003). This figure shows several noise contours that represent same noise levels along either side of road and railway.

Figure 1: 2D noise map (Kluijver and Stoter, 2003)

The noise maps are used as input for the assessment of noise impact on the environment, for example determining the area which is affected by severe noise; determining the number of noise sensitive buildings or the area of natural parks where a certain noise level is exceeded; determining the number of citizens who are annoyed by noise etc. Quantifying the impacts of noise facilitates the comparison of several designs in order to choose the design with the smallest noise impact on the environment.

2.3 Problems of current 2D approach

Most of the noise calculation software calculates noise with the three dimensional data, i.e. heights of buildings, of noise barriers and of other topography are taken into account. Although output of noise calculation software (observation points with calculated noise levels) is described in 3D, most current noise maps are in 2D representing noise levels at one selected height (for example at four meter as required by the European directive). Disadvantage of this 2D mapping method is the lack of insight into the three dimensional character of noise. In many situations noise levels at one particular selected height (for example at four meters) do not provide complete information for assessing noise impact at higher floors of a building.
2D noise maps are used to quantify impact of noise, e.g. overlaid with a 2D building map. This can cause considerable differences between calculated impacts and impacts that (will) occur in reality. The difference is especially large when a building of interest is located close to the noise source or when a noise barrier is present. People living on lower floors of an apartment building benefit more from a noise barrier than people living on higher floors. Therefore number of annoyed people might be overestimated when based on 2D analyses. Summarising, 2D noise maps and 2D analyses are insufficient to discriminate between noise impacts at different heights which is specifically relevant in urban areas. Although current noise simulation models predict noise levels in 3D, noise maps generated in 2D cannot be used directly to study the 3D impact of noise. To use the 3D information in 3D noise impact studies, firstly the output of noise software needs to be processed in 3D.

3. Methodology

This section presents a 3D approach for noise impact studies. It starts with a description of the study area (section 3.1). Section 3.2 presents the calculation method used in this research. The process of selecting the locations of observation points, which is extremely important, is described in section 3.3. Section 3.4 describes how the 3D noise map is generated and section 3.5 describes how the 3D noise map is applied in a noise impact study.

3.1 Study area

The study area is a small part of the city centre of Delft, the Netherlands. Delft is a city of around 95,000 people in the densely populated South Holland province of the Netherlands. The study area is approximately 30,000 m2 and contains about 185 residential buildings with an average height of 15 meters. A 3D city model covering the study area, containing all details of buildings, was provided by Vosselman et al. (2005). The city model, shown in figure 2, is constructed based on an interactive segmentation of the parcel boundaries using several tools for splitting the polygons along height jumps edges. The roads, canals and trees were also reconstructed from the combination of parcel boundaries and laser altimetry data (Vosselman et al., 2005).

Figure 2: 3D city model of study area (Vosselman et al., 2005)

3.2 Noise calculation method

As in other countries, also in the Netherlands calculation methods have been standardised and are commonly accepted as appropriate for noise impact studies after having been validated and calibrated with extensive measurements in 1970s and 1980s (VROM, 1999). From the available Dutch methods the Standard Calculation Method 1 (SCM1) was selected for this research. SCM1 (VROM, 2004) was established by the Ministry of Housing, Spatial Planning and the Environment, according to advise of noise experts and after

extensive testing, for assessing relatively simple noise situations, such as determining noise hot spots, quantifying overall effects and visualising noise levels. SCM1 was chosen since it takes the obstruction of noise by objects such as buildings into account but it is still relatively simple to use, also for non-noise experts. At the same time it meets the requirements for this research (to see how noise studies can be improved by a 3D approach). Other more sophisticated noise calculation methods could also have been used. In this study these methods are not relevant, since the focus is on a method to improve the visualisation and quantification of noise impacts using 3D approach and not to improve the accuracy of the calculated noise level on one specific location.
Inputs for the noise computer model implementing SCM1 are noise sources (location and characteristics), noise propagation factors and observation points. This input information was generated using the 3D city model. Fictitious data were used for traffic intensities. It must be noted that noise levels on 3D observation points are calculated in SCM1 by considering 3D distance and direction of the observation points to the source. Consequently SCM1, as other noise methods, implements a 3D approach for noise calculation.

3.3 Locating 3D observation points

Key issue was to optimally locate the observation points that were used in a second step to produce a continuous noise surface with 2D interpolation (see section 3.4). There are several conditions that prescribe the best location. One condition was that the observation points should be located on the height surface of the terrain since the interpolated noise surface will be draped over the 3D city model in a later stage. Another condition was related to the spatial distribution. In this case in 2D since a 2D spatial interpolation method was used. The decision about the spatial distribution of points for noise simulation is not straightforward. Point density should be sufficiently high to reach adequate accuracy of interpolation results. On the other hand too many points should be avoided in order to considerably reduce computation time of the noise software.
Characteristics of noise propagation can be taken into account in order to optimally distribute points. Noise reduces continuously and logarithmically with distance in absence of obstacles. Furthermore noise reduces discontinuously at obstacles, such as buildings. A previous study showed that point density should be adjusted to these characteristics in order to minimise the error introduced with interpolation (Kluijver and Stoter, 2003). This implies higher density (1 m spacing in the test area) of observation points near the noise sources and buildings and lower density further away from noise sources and buildings (2 m spacing).
Most optimally points should be located at facades of buildings, i.e. with same x,y coordinates but with varying z coordinate. However since 2D interpolation, as applied in this research, can only be used if points are located on different x,y coordinates, points with similar x,y coordinates were simulated by giving them an offset of 0.1 m leaning towards the buildings (see figure 3 (a)). The maximum offset cumulates to about 1m (compare top and bottom of building in figure 3 (a)).
Summarising, there are three types of point densities in the generated observation points data set when only considering x,y coordinates: 1 meter between points near roads and buildings; 2 meter between points further away from roads and buildings (where noise variance is low) and 0.1 meter between points at facades of building (to facilitate 2D interpolation of the observation points). In vertical direction (considering z coordinate) all points are located at 2 meter distance from each other.

Figure 3: (a) spacing of points in horizontal and vertical direction on facades of building, (b) observation points to be used as basis for interpolated noise surface

The total number of points generated (in ArcScene) was around 16,800, see figure 3 (b). The resulting point density is rather high for noise computer models, although appropriate for the densely built study area.

Calculation time was acceptable because of the relatively small size of the study area. Further optimisation of the density of observation points was therefore not necessary but would be necessary in case of a larger area.

3.4 Generating a noise surface by interpolating noise levels

The noise surface was built by interpolating noise levels at known 3D observation points, only taking x,y coordinates of points into account, i.e. using 2D interpolation. The 3D analyst tool of ArcScene was used to generate the noise surface. There is no standard spatial interpolation method that can deal with the logarithmically reduction of noise levels with distance. However there were some prerequisites that motivated the selection of Triangular Irregular Network (TIN) for the interpolation. If noise levels on facades are calculated with noise levels above the road or above buildings errors are introduced due to the high variance in noise level on facades of building. This high variance in 2D (i.e. noise changes quickly with x,y distance) is a result of the effect that noise levels are calculated in the noise computer model based on 3D distance. When projecting these observation points in 2D, sudden change in noise levels occur on a relatively short distance. TIN only takes the closest three observation points into account (distance measured in 2D) when calculating noise level at any unknown point, avoiding that noise values above roads and buildings contribute to interpolated values on facades. Therefore TIN was selected as interpolation method. To proof the assumption that other spatial interpolation methods are less suitable also experiments were done with Inverse Distance Weighting (IDW), Natural Neighbourhood and Kriging. For an explanation of the principles and advantages and disadvantages of each interpolation method, see Watson (1992).

3.5 3D noise impact study

After the interpolation the noise surface is draped over the 3D city model to generate the 3D noise map. This is done in ArcScene. The noise surface is made transparent so that the buildings can be seen through the surface. Also contours are generated which are extended towards 3D by draping them over the city height model. Using this methodology the 3D noise map is easy to construct and suited for quantitative analyses such as for finding noise hot spots, calculating area that are effected by high noise levels, and estimating population annoyed by noise. To improve the reality look virtual reality functionalities could have been applied such as textures (see also Wing and Kwong, 2006). One should however realise that the more realistic the visualisation looks the more accurate decision makers expect it to be. This expected accuracy does not always coincide with the intended accuracy of the noise representation. The 3D noise map is used as input to quantify noise impact in 3D using basic spatial analysis tools in ArcScene.

4 Results

In this section the results of the 3D noise map are presented. Section 4.1 presents the results of the noise calculation. The 3D noise map is assessed in section 4.2 and the improvements of the 3D noise map compared to the 2D approach are presented in section 4.3 by applying it to some aspects of a noise impact study.

4.1 Accuracy of noise calculation

The offset of 0.1 m for points on facades introduces an error, which was analysed to see if the error is acceptable. At a distance of 5 m from the centre of the road the error is ±0.7 dB(A) which is only minor compared to the calculated difference of ±10 dB(A) between noise levels at the top and bottom of the building (see figure 4).

Figure 4: Observation points near buildings with computed noise levels

Furthermore this difference is not audible for human beings. For general noise impact studies, where the selected SCM1 method is designed for, this inaccuracy is acceptable. However when complying with noise limits a minor difference could be relevant and other more accurate calculation methods should be applied. As stated before an accurate calculation method is not the aim of this research

4.2 Results of the 3D noise map

To assess the accuracy of the interpolated noise surface, cross validation was applied (Davis, 1987). Observation points were removed before interpolation and interpolated values on these points were compared to values calculated by the noise software. This yielded a mean error of 0.3 dB(A) and was therefore also acceptable. This implies that 2D interpolation can be used for building 3D noise map.
The result of the 3D noise map integrating the noise surface using the TIN interpolation method and the 3D city model is shown in figure 5. From figure 5 it can be seen that the 3D noise map is able to properly process and visualise the 3D output of noise calculation software. The 3D representation offers insight into the impact of noise at any particular height on the terrain surface and on facades of buildings: high noise levels occur on road surfaces and low noise levels occur on top and backside of buildings.

Figure 5: 3D noise map obtained with TIN interpolation

2D noise contours (interval of 1 dB(A)) were generated and projected on the city model to extend them towards 3D. The IDW noise surface was generated with power 2, search radius 2 m, and cell size 0.1 m. The cell size of 0.1 m was chosen to cover the high point density on facades of buildings when only considering x,y coordinates. Contours from TIN interpolation method and IDW interpolation method at facades of buildings (location with highest variance in noise levels) are shown in figure 6 (a) respectively 6 (b). Noise observation points are shown as well.

(a)

Contours generated from TIN interpolation method

(b)

Contour generated from IDW interpolation method

Figure 6: Noise contours of two interpolation methods projected on 3D city model

As expected IDW interpolation produces irregular contours. This does not reflect the real noise behavior since noise levels reduce similarly with decreasing distance if no other variables, such as noise barriers and absorption properties, are met or changed. On the contrary TIN contours do show straight contours, as can be seen in figure 6 (a). Other interpolation methods (Natural Neighbourhood and Kriging) yielded similar results as IDW.
These irregular IDW-contours were found on locations were noise reduces very fast with distance (when only considering x,y) represented by high point density, as is the case on facades. IDW (as the other alternative

methods) is based on one search radius for the whole area, by which values on roads and above buildings are used for calculating values at facades. This causes the faulty effects on locations where noise reduces very quickly with distance, as shown in figure 6 (b) and 7 (b).
TIN takes only three observation points into account when calculating a value at an unknown location. It is appropriate for situations with high noise variance represented by high point density because it generates more triangles with relative small areas at these locations (see figure 7 (a)). As a consequence noise levels on facades are calculated based on observation points on facades only and it is avoided that observation points on roads and above buildings contribute to interpolated values on facades. This explains why TIN is the most optimal method for generating the 3D contours for the 3D noise map, using 2D interpolation applied to 3D observation points.

(a)

(b)
Figure 7 (a): TIN can deal very well the spatial irregularly distribution of observation points on facades of buildings, (b) results of noise contours based on IDW (viewpoint is from above in both examples).

4.3 Results of applying 3D noise map to noise impact study

The results of the 3D noise map with respect to improved 3D functionalities were tested by applying it to different aspects of noise impact studies. The aspects that are addressed here are:
- Assessing reduction of noise levels by noise barriers
- Estimation of population annoyed by high noise levels

Assessing reduction of noise levels by noise barriers
A 3D noise map was produced with the methodology described in section 3, using information on seven fictious noise barriers in order to assess the 3D impact of several characteristics of noise barriers. Figure 8 shows the impact of the different noise barriers varying in height, width and distance from the road. Details of the different barriers are shown in the bottom left of figure 8.

Figure 8: Effect of noise barriers represented in 3D noise map

The first three barriers (a), (b), (c) are of height 3 m and located at a distance of 3 m, 6 m, respectively 9 m from the road. As can be seen in figure 8, the effect of the barrier reduces when the distance of the barrier to the road increases. Furthermore it shows that there is no effect of the barriers on higher floors.
The next three barriers (d), (e), (f) are of different heights (2 m, 3 m, and respectively 4 m) and located at equal distance of 5 m from the road. Figure 8 shows that noise reduction due to the noise barriers increases when the height of the barrier increases. Still no effect of the noise barrier is found at higher floors. Barrier (g) is located where there is no building. Barrier (g) shows therefore the effect on the ground surface.
Table 1 shows the noise impact on the facade of the building just behind barrier (a) with height 3 m and located 3 m from the road. From this table it can be seen how the noise barrier reduces noise levels at different heights. This case study shows that a noise barrier should be high enough and sufficiently close to the road to have a reducing effect for all floors. A 2D map representing noise levels at only one height (e.g. 4 m) cannot

provide this information. In case of 2D map, noise levels on lower floors could be overestimated and on higher floors underestimated.

Height above the ground surface (m)	Without noise barrier (dB(A))	With noise barrier dB(A)	Effect dB(A)
2	59	38	-21
4	58	41	-17
6	56	44	-12
8	55	46	-9
10	53	48	-5
12	51	51	0

Table 1: Noise levels at different heights on facade of building with and without noise barrier (a) as indicated in figure 8

Estimation of population annoyed by high noise levels

For estimating population annoyed by noise, the considered threshold of annoyance is 55 dB(A). This noise level is considered as hazardous by (WHO, 1999). Table 2 shows the comparison of annoyed population estimation using 3D noise map (taking floors of buildings into account) and using a 2D approach at a height of 4m. For the 3D noise map calculation, population numbers were assigned to 3D points and for the 2D approach, population numbers were assigned to 2D points. These points are selected in such a way that they coincide with centres of living units. Based on the number of population points covered by surfaces with high noise levels in 3D case and by areas with high noise levels in 2D case, population annoyed by noise was estimated.

The results in table 2 show that annoyed population calculated using the 3D noise map is considerably less than using the 2D noise map. This is because in case of 2D assessment all floors are considered to be effected by the same noise level, even though the noise levels are calculated for one specific height (i.e. 4 m). In reality there are several floors above 4 m and only one floor below 4 m. Floors above 4 m are effected by lower noise levels than at 4 m (when there is no noise barrier) since noise levels decrease with distance from the road and therefore with height. Consequently the 2D assessment results in an overestimation of the number of annoyed people. From this case study it can be concluded that the 3D noise map analysis provides a much more accurate estimation of annoyed population than the 2D noise map analysis.

Noise map used	Population in numbers
2D noise map	11000
3D noise map	7200

Table 2: Population annoyed by noise levels > 55 dB(A)

5. The accuracy issue of noise modeling

Accuracy can be defined as “the extent to which an estimated data value approaches its true value” (Aronoff, 1991). In case of addressing accuracy aspects of noise modelling, the whole process of a noise application - from data collection and prediction to applying it for a specific purpose - should be taken into account. Accuracy is influenced at each operation such as during generation of observation points, spacing of points, noise calculation, spatial interpolation and analysis. It is not useful to put effort in improving accuracy of calculated noise levels, if these levels are only used in combination with low-resolution data on population for global impact assessment.

In noise applications, accuracy of three outputs is of interest:

1. Accuracy of output of the noise calculation method

2. Accuracy of interpolated noise surface
3. Accuracy of output of noise impact assessment

In this section, we will elaborate on how accuracy relates to these three outputs in respectively section 5.1, 5.2 and 5.3.

5.1 Accuracy of noise calculation method

The noise calculation method used in our research, is specifically designed to assess overall noise impact in simple situations. If more accurate information is needed, a more advanced calculation method can be used, for example noise calculation method 2 (SCM2). In SCM2 all factors affecting noise levels including reflection and obstruction of sound between buildings are taken into considerations. However the disadvantage of this method is that it requires high computation. In addition it is a time consuming approach to collect all detailed input information, such as XXXHENK??. Since SCM2 yields more accurate noise levels, SCM2 is applied when more accurate noise levels are needed, for example to comply with noise limits by insulating houses. Since much money is involved in the insulation of houses it is important to precisely indicate which houses are exposed to high noise levels.
Validation of noise levels by field measurement XXHENKXX

5.2 Applying surface and 3D interpolation to improve accuracy of noise surface

In the research presented in section 3 and 4, a simple technique was used to generate the noise surface, since the aim was to show how noise impact studies can be improved when a 3D noise map is used instead of a 2D noise map. Although the error analysis showed that the results of our approach are acceptable, an important next step is to improve the accuracy of the 3D noise map. This can be accomplished by applying 2.5D and even 3D spatial interpolation to the output of noise calculation. Experiments were done with the interpolation method of Boissonat and Flötotto (2002), implemented in CGAL to interpolate noise levels over a surface. However a closed surface is formed with the algorithm which is not appropriate for the city model in our study. In addition also experiments were done to produce a solid model of noise levels by interpolation of noise levels in 3D. A noise surface following the terrain can be selected from this solid model to generate the 3D noise map to be used as input for 3D noise impact studies. This section presents the results of the solid model.

Observation points for 3D interpolation

For the full 3D noise representation a 3D raster of points was generated covering all space between and touching buildings. For 3D interpolation, points can have same x,y but different z coordinates. Therefore it was not necessary to generate points with offsets as shown in figure 3 (a). The 3D points are distributed evenly with equal intervals in both horizontal and vertical directions (2 m) in ‘lines’ parallel to the roads. Noise contours are expected to be parallel to the roads and data points located in a pattern parallel to the road can reflect this behaviour most optimally. Obviously care was taken not to place points inside buildings, because buildings act as blocking objects in the model and these points would produce low levels which are not representative for the levels on the façades of the buildings. The total number of observation points is 19,500 (16% more than in case of only locating points on the terrain surface, requiring XXX% more computing time XXHENK).

3D interpolation

Currently very few commercial GIS software systems provide tools for 3D interpolation. Some of the software systems that do offer 3D interpolation tools are GOCAD, Environmental Visualization Systems (EVS), Rockworks, GRASS and FIELDS. Most of these software systems are for hydrology, geochemical, geophysical, geotechnical or lithology studies and they are based on borehole data. In these software systems the solid model algorithm is implemented to interpolate attribute values from depth intervals of strata such as soil, rock, or ground water. Therefore these could not be used to interpolate point data as produced by the noise software. It should be noted that GRASS does offer point based interpolation tools. However after some initial tests with GRASS software (GRASS-5.4), it was concluded that it could not be used in our research due to the limitation of input data points (maximum of 700 points), which is expected to be solved in next version of GRASS.

There are also examples of non-commercial software tools developed by individuals aiming at specific purposes. Since most of them are meant to prove concepts in scientific research, it is hard to reuse the code. An example is the 3D Natural Neighbourhood interpolation method implemented in Delphi language by Ledoux and Christopher (2004). This technique was tested in our research. The code is able to perform 3D interpolation but since the amount of input and output data is limited, it could also not be used in our research. Finally the FIELDS software (Field Environmental Decision Support tools, extension of ArcView 3.5; FIELDS, 2007) was applied successfully in our research. In the 3D IDW method implemented in FIELDS the searching ellipsoid-body is used to find the known points that will contribute to the interpolated value. 3D distance is used to determine the weights of the known points. The 3D IDW interpolation was performed with IDW power 2 and with maximum points of 10 in each ellipsoid-body. The voxel size chosen for the solid model is 2 m because this reflects the distance between observation points. As in 2D IDW, the disadvantage with this method is when the data varies greatly in one dataset because a fixed major and minor radius of ellipsoid will not necessarily be appropriate everywhere in the dataset.

The result of the 3D interpolation is a solid model which can be analysed by slicing the model. Due to limitation of software it was not possible to select a surface representing noise levels following the terrain. Therefore it was not possible to display the 3D city model together with the results of the 3D solid noise model and to use it to produce a 3D noise map. However, it was possible to clip the model using the polygon layer of roads (figure 9).

Figure 9: Volumetric view of noise levels on the road surface of study area.

Longitudinal and transverse cross sections of the 3D noise representation were generated and are shown in respectively figure 10 (a) and (b). From Figure 10 it can be concluded that the 3D noise representation clearly shows the pattern of noise levels above the road surface in all directions. Using this model noise propagation in three dimensions can be analysed; Figure 10 (b) shows high noise levels at the middle of the road and gradually reducing noise levels with increasing 3D distance from the centre line of road.

Figure 10: Cross sections of the solid noise model: (a) section AA in figure 9; (b) section BB in figure 9.

Cross validation was carried out to assess the accuracy of the interpolation. The results showed that mean error of 3D IDW interpolation method are very low when compared to mean error of 2D IDW interpolation method (0.000039 compared to 0.27). However the values are hard to compare since the approaches differ in some fundamental aspects such as the cell sizes. Larger cell sizes tend to average values leading to closer results when performing cross-validation.

From our experiments we can conclude that a 3D solid model reflects the three dimensional character of noise in all dimensions, not only on the terrain surface. Therefore the 3D model is specifically suited for noise experts to improve insight into 3D noise propagation and the way this behaviour is implemented in current noise computer models.
Future research can focus on how to convert the noise levels from the solid model into an environment where the noise levels can be combined with other spatial and non spatial data to perform noise impact studies. Concerning the FIELDS software, there were no tools available for spatial analysis with the solid model, generating 3D noise contours, and to create neither a noise surface nor 3D contours following the terrain surface.

5.3 Accuracy of noise impact study

In the two examples of noise impact studies described in section 4, it was shown that in certain situations noise impact assessment using a 3D noise map provides more accurate results than using a 2D noise map. This is because the 3D noise map facilitates distinguishing between noise impacts at several heights.
In that respect the results of our study show that a 3D approach gives relatively more accurate results when 3D effects of noise are relevant. However, as in 2D, it is important to perform error-analysis by considering the accuracy of all input data to be able to determine the absolute accuracy of the noise impact results. For example postal areas are often used as population distribution source, providing global figures on annoyed population. In an initial stage of an infrastructure construction project, such a global assessment may be sufficient. In a latter stage, more detailed and accurate results might be necessary. In both cases however results should be accompanied by information describing accuracy of the results, in order to assure that global results are not misused to plan detailed measurements for reduction of noise levels.

6. Conclusions

In this paper a research was presented that shows how impact studies of continuous spatial phenomena, such as air pollution, soil pollution and noise, can be improved by applying a 3D approach to the output of software that predicts the spatial phenomenon on 3D observation points. In the study noise is used as example.
In section 2 the demand for a 3D approach of noise impact studies was described based on a review of existing approaches. In section 3 a new approach was proposed in order to appropriately address the 3D aspect of noise when visualising and assessing impact of noise. The proposed concept was proven by applying it to a sample noise impact study in section 4.
A 3D noise map can be generated by integration of a 3D city model with a noise surface representing noise levels on a terrain surface. For producing the noise surface, TIN interpolation was applied to 3D observation points. The noise surface and generated noise contours were draped over the 3D city height model to obtain a 3D noise map. From the results it can be concluded that this approach serves its purposes also with respect to the accuracy required by the specific application, which is visualising and quantifying overall noise impact in 3D where 3D effects are relevant.
The 3D noise map offers insight into the 3D noise situation where 2D noise maps have limitations. Current noise simulation software already has a 3D approach in predicting noise levels. The 3D noise map provides the possibility to actually process and visualise this 3D information. As a result more accurate assessment of noise impact is possible in particular when different floors of a building close to noise sources or noise barriers are considered, which is specifically relevant in urban environment. Since a 3D noise map is easy to ‘understand’ they are also beneficial for communication purposes with the public in city planning processes.

The noise application in this research specifically aims at improvement of the overall picture of noise impact. Therefore improving the accuracy of calculated noise levels for specific locations was not the main concern. However since accuracy is an important issue in noise modelling, a section was dedicated to improving accuracy of noise calculation, of interpolation by applying a 3D interpolation method, and of noise impact studies. From the experiments with 3D noise interpolation, it can be concluded that the results look promising. Although a method to extract a noise surface or noise contours following the terrain is still lacking. Such a surface and these 3D contours form the core of a 3D noise map. Ambitions for further improving accuracy are obviously supported by the authors but not without emphasising the need for error assessment and presentation of the uncertainties in all phases of the process, also with respect to the purposes the study has to serve.
The methodology presented in this paper can be applied to other continuous spatial phenomena as well so that it meets the more general problem of how to represent 3D aspects of environmental impact studies.

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Figures

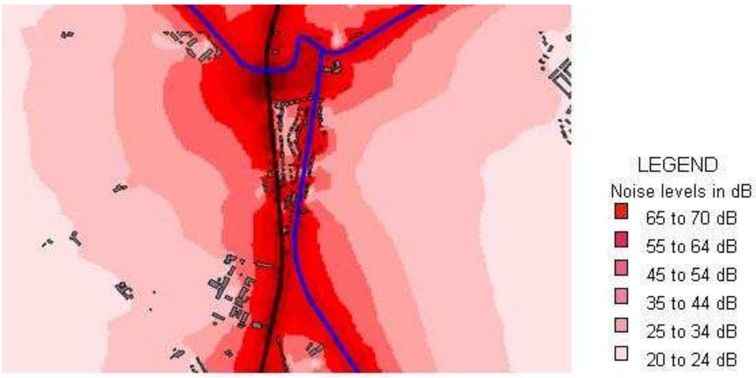


Figure 1: 2D noise map (Kluijver and Stoter, 2003)

Figure 2: 3D city model of study area (Vosselman et al., 2005)

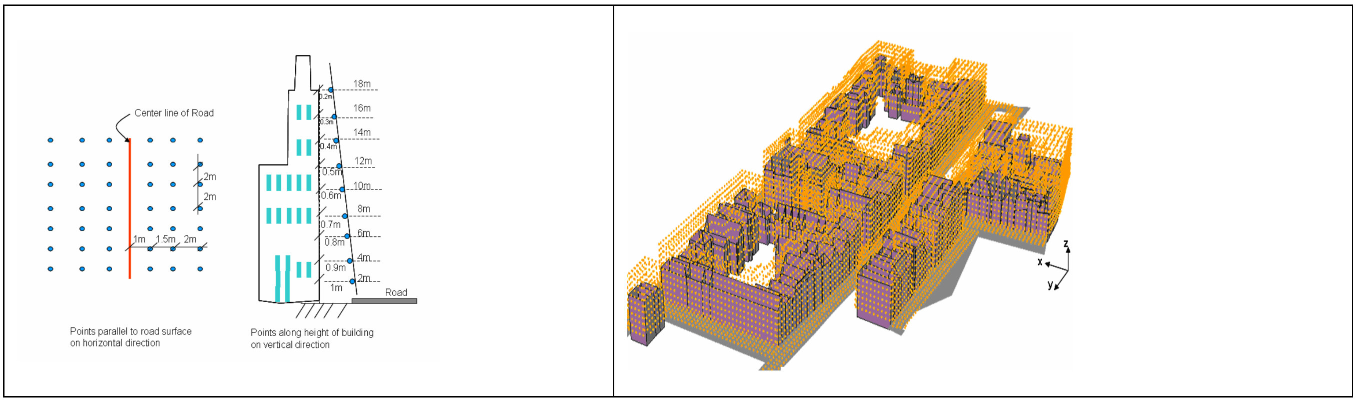


Figure 3: (a) spacing of points in horizontal and vertical direction on facades of building, (b) observation points to be used as basis for interpolated noise surface

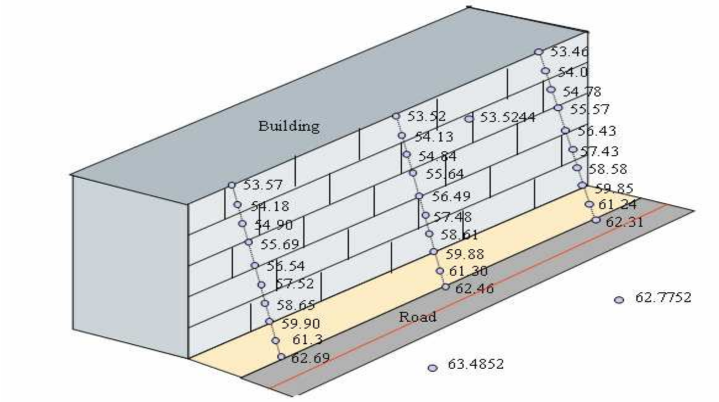


Figure 4: Observation points near buildings with computed noise levels

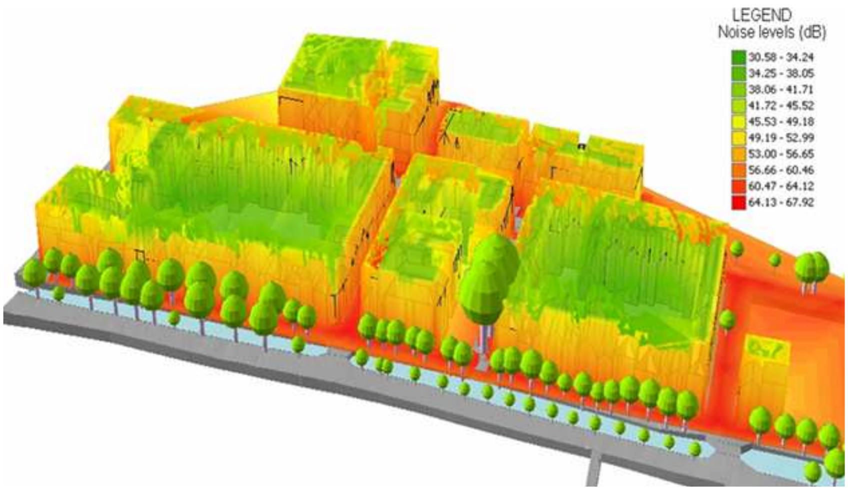
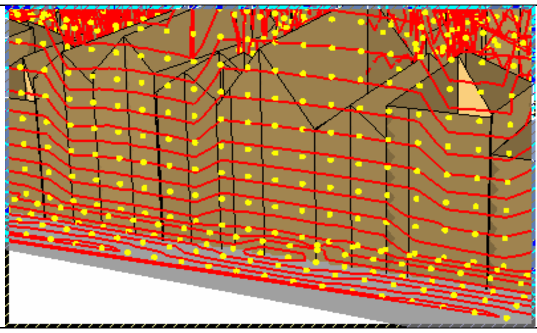


Figure 5: 3D noise map obtained with TIN interpolation

(a) Contours generated from TIN interpolation method	

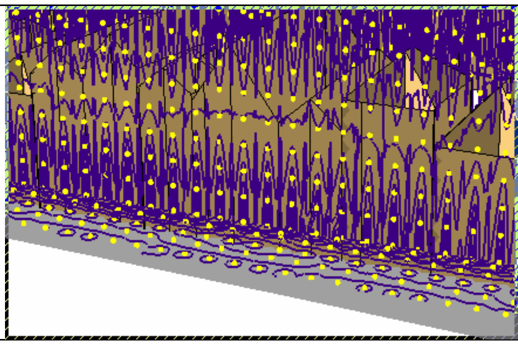
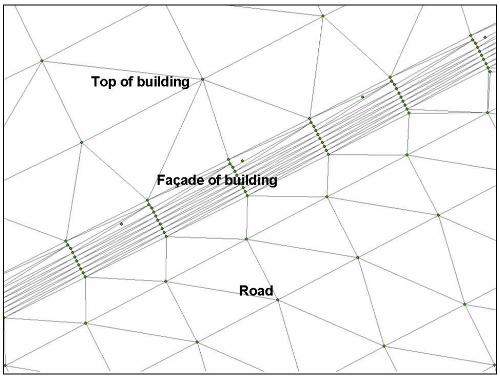
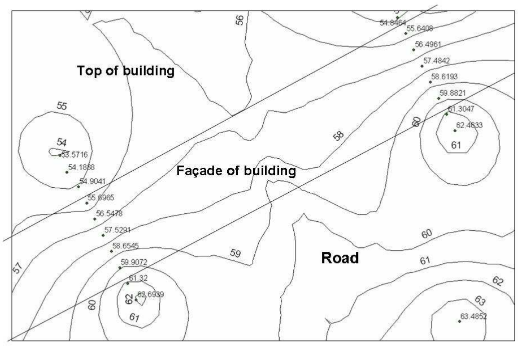
(b) Contours generated from IDW interpolation method	

Figure 6: Noise contours of two interpolation methods projected on 3D city model



(a)



(b)

Figure 7 (a): TIN can deal very well the spatial irregularly distribution of observation points on facades of buildings, (b) results of noise contours based on IDW (viewpoint is from above in both examples).

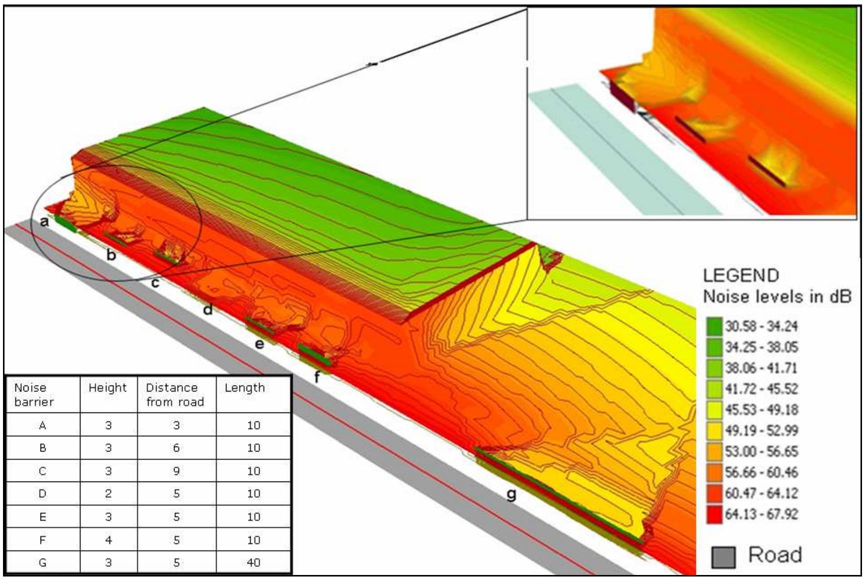


Figure 8: Effect of noise barriers represented in 3D noise map

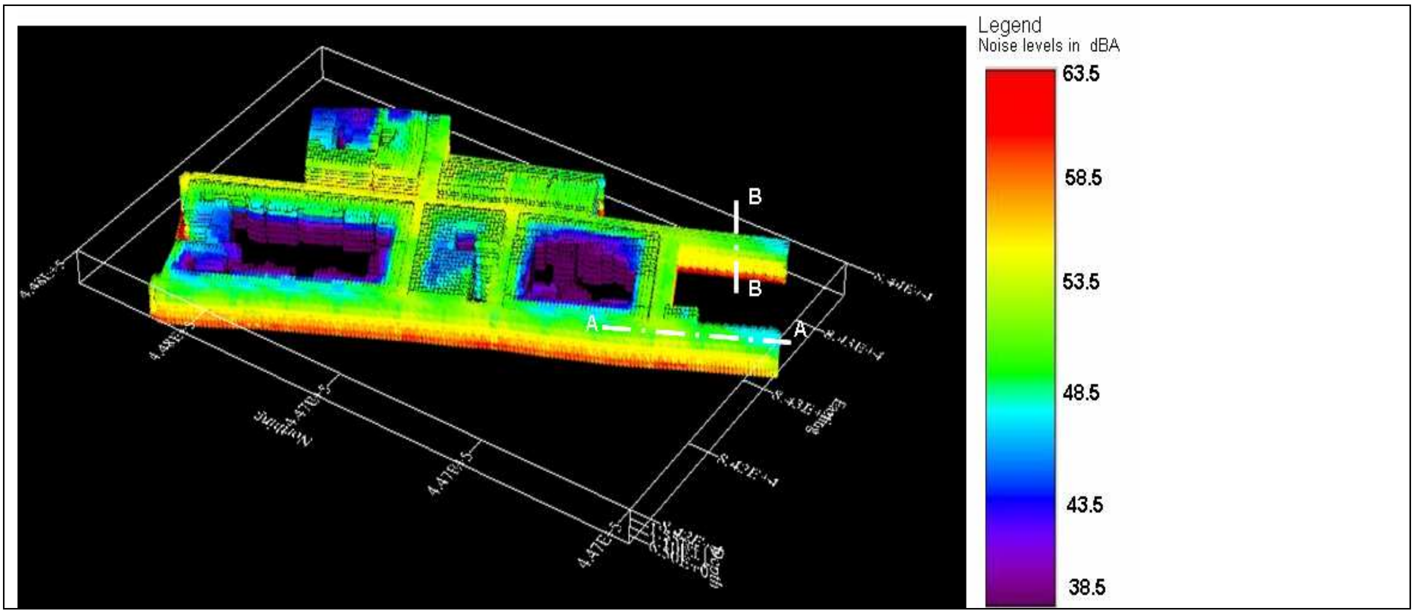


Figure 9: Volumetric view of noise levels on the road surface of study area.

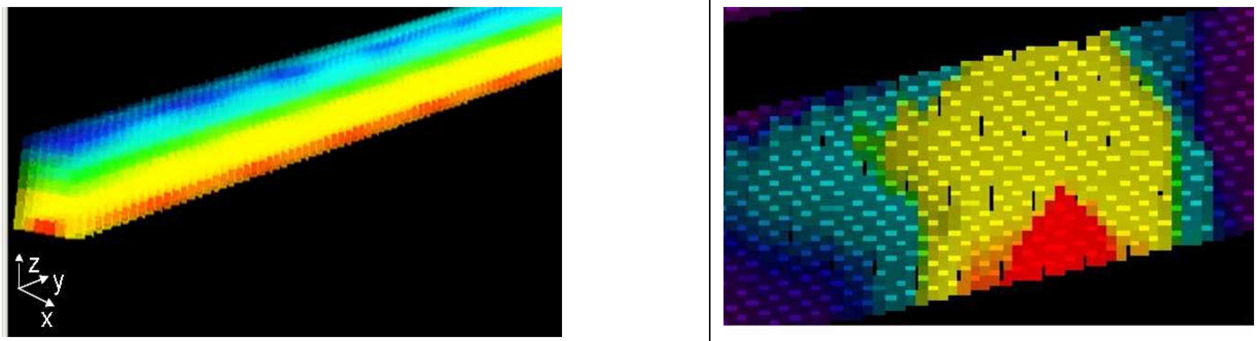


Figure 10: Longitudinal cross section (section AA in Figure 11) (a) and transverse cross section (b) of noise on the road surface (section BB in Figure 11)