Smart sound monitoring for sound event detection and characterization

Bert DE COENSEL[1]; Dick BOTTELDOOREN[2]

Ghent University, Belgium

ABSTRACT

As there is little doubt that the perception of one's acoustic environment is mainly driven by noticed sound events, an environmental sound policy approach with a focus on the local urban neighborhood scale should address all noticeable sound events. These sound events have in common that they are not easily predictable, and that they show a very strong spatial variability. Dense urban sound monitoring networks are therefore well suited to assess such sound events, and could support a micro noise policy based on targeted action plans. This paper reports on the Smart Sound Monitoring project that was carried out on the Katendrecht peninsula, located within the Rotterdam harbor zone. A distributed measurement campaign using 12 intelligent sound measurement devices, active during several months, was carried out in combination with an online, continuous survey. Through the latter, inhabitants of the case study area were encouraged to signalize, instantly and triggered by perception, salient sound events that occurred around their dwelling, and to report their general sleep quality on a daily basis. The presented approach can be used to relate the occurrence and acoustical characteristics of sound events to reported events and sleep quality.

1. INTRODUCTION

Since the publication of the European Directive 2002/49/EC on the assessment and management of environmental noise (1), EU noise policy and many national policies on environmental noise are mainly based on (yearly averaged) energy equivalent noise levels, such as L_{den} or L_{night}, calculated using standardized noise mapping. The estimated risk for being highly annoyed by noise in and around the dwelling is based on L_{den} *exposure-effect relationships* that are aggregated from many local studies, e.g. as in (2). Similarly, the estimated risk for reporting sleep disturbance is related to the nightly 8-hour energy equivalent noise level, L_{night}. These exposure-effect relationships relate to self-reported retrospective annoyance and sleep disturbance.

Sound intruding from outside the dwelling is almost always disturbing, since it penetrates the privacy of the dwelling uninvited. Noticing the sound is often sufficient to cause at least some level of annoyance (3). The activity of the listener, personal factors such as lifestyle and noise sensitivity, and coping capabilities (4) are some of the factors that modify the resulting annoyance. In the simplest models, noticing a sound depends on the relative level of that sound compared to the background or the emergence of the sound event above background. This leads to indicators such as the number of sound events, the traffic noise index TNI (5), etc. More advanced models estimate how strongly a sound stands out of the background, based on spectro-temporal variability or so-called *saliency*. Also noise-induced sleep disturbance, which includes remembered awakenings and difficulty of falling asleep, is largely sound event driven (6). Even a physiological response that is not perceived consciously may deteriorate sleep quality and thus lead to overall fatigue (7). The pattern and time of occurrence of noise events during sleep, and to some extent their meaning, is of relevance, but no integrating models accounting for these effects are currently available.

Exposure-effect relationships based on equivalent levels are applicable for strategic planning and for the assessment and management of noise caused by major traffic infrastructure. However, local noise disturbance is not captured very well, and a policy exclusively based on mapping of equivalent noise levels will fail to capture many of the noise complaints. From the above it becomes clear that an appropriately focused environmental sound policy approach needs to address *all noticeable sound events*, such as from loud vehicles, delivery, loud voices etc., which are not easy to predict, and which show a very strong spatial variability.

---

[1] bert.decoensel@intec.ugent.be

[2] dick.botteldooren@intec.ugent.be

Figure 1 – Aerial photograph of the case study area "Katendrecht", with the locations of the 12 measurement points (Source: Google Earth).

Recent advances in the development of low-cost computing devices and microphone systems, and the increasing availability of (wireless) internet access, form a technological push for the use of distributed sound measurement networks. Moreover, by introducing machine listening into the realm of environmental noise measurement, novel perceptually inspired models and techniques are increasingly being applied to analyse the staggering amount of data generated by acoustical sensor networks. Meaningful information extraction that goes beyond calculating sound levels can hereby be performed, such as sound recognition, source localization and constructing dynamic noise maps that are updated in near real-time. The use of a dense urban network of intelligent sound measurement devices therefore allows to observe the occurrence and assess the characteristics of sound events in urban context in much more detail as compared to conventional noise mapping and local off-line sound measurements. Ultimately, this *smart sound monitoring* approach allows to better predict the prevalence of annoyance and sleep disturbance in local urban environment, and could support a micro noise policy with a focus on the local urban neighborhood scale, based on more targeted noise action plans. Micro noise policy measures based on smart sound monitoring that could be envisaged are mainly guided by the local situation and the creativity of governance; some examples are dynamic traffic management or anomaly detection in noise from industrial plants or from off-peak quiet delivery to shops.

This paper reports on the Smart Sound Monitoring project that was carried out on the Katendrecht peninsula, located within the Rotterdam harbor zone, from August to December 2013. The aims of this pilot study were (i) to demonstrate how, in a cost-effective way, objective measurements (using a spatially detailed sound monitoring campaign) and subjective measurements (using an online noise survey) could be combined, (ii) to use this system to better detect and characterize sound events occurring within the study area, and (iii) to train the system's capabilities to detect and identify sound events and ultimately to predict the impact of environmental sound on well-being and health, such that in future, reporting by inhabitants would no longer be necessary. In Section 2, a brief overview of the case study area is given; in Section 3, the measurement and survey methodology is explained in detail; in Section 4, the results of the study are discussed.

2. CASE STUDY AREA

The case study area "Katendrecht" consists of a mainly residential peninsula located within the Rotterdam harbor zone, just south of the Rotterdam central business district. It has an area of $1.18\,\text{km}^2$ and has 4445 inhabitants (as of Jan 1, 2012). Figure 1 shows an aerial photograph of the area, together with the locations of the 12 measurement points (see below). Due to the low amount of traffic on the roads inside the peninsula, and the relative remoteness of the peninsula to the other parts of the city, background levels in the area are relatively low, so one would assume that the area is relatively tranquil. However, a number of sound sources located on the peninsula and its surroundings give rise to stationary noise as well as sound events.

The northern side of the peninsula mainly consists of an industrial plant (near measurement point 211) and a public park. Ships passing by along the Nieuwe Maas, and loading and unloading of trucks near the industrial plant, are the main noise sources at the northern side. At the southwestern side, a large museum/restaurant

Figure 2 – Selection of photographs taken within the case study area "Katendrecht": (left) impression of the region along the southern side (measurement points 202–206, 213); (middle) impression of the region at the northwestern edge (measurement points 208, 209, 212, 220); (right) impression of the region at the northern side (measurement points 210, 211).

Figure 3 – Example of a sensor node, placed on the windowsill of a dwelling.

ship is docked, causing some sporadic traffic noise. The southern side of the peninsula, mainly lined with dwellings, is directly exposed to the Maashaven, where (un)loading of ships (mainly corn) results in regular periods of constant noise exposure. Finally, the main road into the peninsula carries some trucks (about 200 movements/day) with the industrial plant on the peninsula as their destination. In order to give an impression of the surroundings, Figure 2 shows a small selection of photographs taken within the study area.

3.   METHODOLOGY

The general approach followed in this pilot study consists of the combination of a smart sound monitoring campaign (Sections 3.1 and 3.2) and an online, continuous noise survey (Sections 3.3 and 3.4).

3.1   Distributed sound measurement

The environmental sound inside the case study area was monitored using 12 cost-effective sensor nodes (Figure 3), placed at the façade of the dwelling of volunteers living in the area. The sensor nodes consist of a single board computer, equiped with a CF card, a sound card, an ethernet card, and a microphone, all put inside a weatherproof housing. The sensor nodes are fully *plug-and-measure*: installation only involves connecting the device to the power outlet and to the internet (the volunteers agreed to make their internet connection available), there are no buttons or displays on the sensor node.

When plugged in, sensor nodes continuously measure 1/3-octave band levels, with a temporal resolution of 125 ms. These levels are then sent over the internet to the server infrastructure located in Ghent, Belgium, where the data is further processed. Sensor nodes are also able to record and transmit short audio fragments if triggered, which may aid sound recognition (see below). The data communication has some robustness
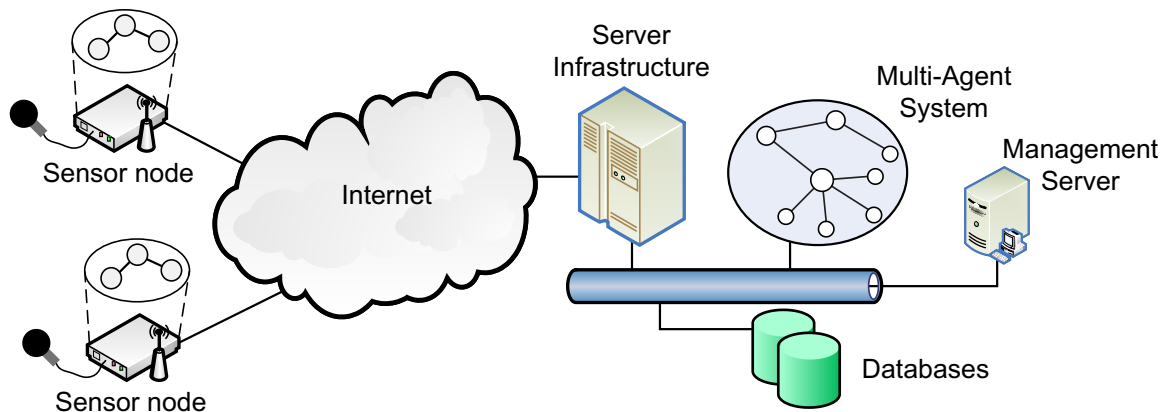
Figure 4 – General overview of the smart sound monitoring sensor network architecture.

built-in: if the internet connection fails for some reason, the nodes save their data internally, and send them in one batch once the internet connection is back online. Further processing of the recorded sound levels is carried out using an *agent-based approach* (see Section 3.2) running in a virtualization layer, by which all intelligence and control is situated at the server side. Calculations performed by agents are scheduled using a task management server; results calculated by these agents are then stored in a so-called *warehouse database*, which can be queried by visualization software through a dedicated interface layer. Figure 4 gives an overview of the general sensor network architecture.

3.2   Agent-based sound analysis

For all data available for each sensor node, a range of basic acoustical indicators is calculated on a 15-minute basis, using an agent-based system. These indicators include a.o. $L_{\text{Aeq,15min}}$ and the standard deviation of the level, percentile levels, the number of sound events, indicators for the temporal structure of the sound (8), psychoacoustic indicators (loudness, sharpness), spectral indicators such as the center-of-gravity of the average 15-minute spectrum, the presence of tonal components, and aggregated indicators.

Next to calculating basic acoustical indicators, agents may also perform more complex tasks, such as *sound recognition*. Dedicated agents hereby perform a number of steps, for each node separately. First, on the basis of the continuous 1/3-octave band spectrum, a set of biologically motivated features is calculated, which encode loudness, temporal and spectral structure of the sound. Subsequently, features are grouped based on co-occurrence, in a continuous and unsupervised way, using a self-organizing map (SOM) (9). When trained for a sufficiently large amount of time (typically at least a few weeks), regions in this node-specific map start to correspond to specific types of sounds that occur in the vicinity of the node. In order to cope with the large fraction of the time that only background sound is audible without any discernable sound events, the learning rate of this SOM is modulated by saliency. In a last step, a multi-layer neural network is used to couple concepts (i.e. linguistic labels) to the regions in the SOM (10). When a specific concept is activated, based on activation in a region in the SOM, the presence of a particular sound is detected and a label (e.g. "car", "bird", "voice"...) is attached. It may occur that a specific region in the SOM is activated which does not give rise to an activated concept, which implies that an up to then unknown sound is present. This may trigger sound recording for the sensor node; the recorded audio fragment may then be used for supervised labeling and thus improving the sound recognition system.

3.3   Online survey

In parallel with the smart sound monitoring campaign, an online survey into the perception of the environmental sound inside the case study area, and into the liveability of this neighborhood in general, was conducted among its residents. The survey consisted of two parts: an *intake questionnaire*, which contained mostly retrospective elements, and a *continuous questionnaire*, which contained instantaneous elements. The questionnaire system was implemented as an integrated online portal, written in PHP/MySQL, and was made available at http://www.asasense.com/katendrecht.

The *intake questionnaire* was administered at the moment that participants agreed to contribute to the survey. The purpose of the intake questionnaire was to obtain information on the general perception of the living environment, before attention was focused on noise, together with all relevant demographic information. Only people living inside the case study area were able to participate. The intake questionnaire consisted of questions on socio-demographic data (age, gender, education, employment, social situation, health and hearing problems), on the dwelling (address, type, orientation, quiet side), on general noise annoyance (standard ISO

Figure 5 – Screenshot of the sound event report window. A similar page was constructed for submitting sleep diary records.

question), on low frequency noise (11), on general sleep quality (12), on noise sensitivity (13), and on personal wellbeing (14). Once participants completed the intake questionnaire, they received an account, with which they could log into the system at any time, and participate in the *continuous questionnaire*. Two types of continuous questionnaires were constructed: a *sound event report* and a *sleep diary*.

With the *sound event report*, participants could signalize particular events or changes in the sound environment around their dwelling. A sound event was defined as any event that draws attention to the sound outside the dwelling. This could have been the presence of a new sound, a change in the sound environment (e.g. a sound that appeared or disappeared), sounds that were suddenly very loud etc. The motivation for filling in a sound event report was *perception driven*: when participants were at home and they perceived a sound event, they should report this by logging into the system and filling in the short questionnaire. Participants were allowed to freely report sound events whenever and as much as they liked, but they were instructed to report as quickly as possible, and no later than 15 minutes after the sound event occurred. If they could not report an event within this timeframe, they were instructed to not bother anymore. The sound event report contained an open question on the type of sound event, questions on the audibility and pleasantness of the sound event, and questions on the activity and the location of the person at the moment the sound event occurred. Care was taken that answering all questions would only take one minute at most. Figure 5 shows a screenshot of the sound event report window.

With the *sleep diary*, participants could periodically report their overall sleep quality, preferably every day, in the morning. Participants were asked to keep track and report spontaneously every day. It may have happened that a participant did not have time to fill in the sleep diary; in order to keep track of all days, the participants were able to fill in a report for the previous night and the night before. It was decided that it was best not to go any further back in time, because of depending too much on the memory of the participants might have a negative influence on the accuracy of the data. The sleep diary questionnaire consisted of general questions about the duration of the sleep period, followed by 10 questions on the sleep quality of the previous night, which were based on the questions asked in the intake questionnaire regarding sleep quality.

3.4   Coupling of acoustical data to survey data

For each sound event report, and for each reported sleep period, a dedicated software agent fetched and processed the most relevant acoustical data (from the nearest sensor node). The following real-time procedure was implemented in the agent-based framework: based on the address of the user reporting, data for those nodes that are located within a distance of 300 m is queried (node by node, sorted by distance) until a node is found that has measurement data for the time period considered. This procedure allows to account for sensor nodes that are temporarily offline, for nodes that are being added to the network etc. For sound event reports, acoustical data for 45 minutes before to 15 minutes after the event report was fetched (i.e. 1 h in total). For the sleep diary entries, acoustical data for the full reported sleep period was fetched.

4.   RESULTS

4.1   Participatory process

Recruitment of volunteers for installing a sensor node at their dwelling was carried out through an information meeting with interested inhabitants, advertisements in local newspapers, and by handing out flyers. An overview of the locations of all sensor nodes that have been installed over the course of the pilot project, 12 in total, can be found in Figure 1. Within this participatory process, sensor nodes were handed over to interested inhabitants of the case study area for self-installation. The plug-and-measure approach proved to be successful: sensor nodes were usually installed and active shortly after delivery. Another important parameter is the reliability of data collection, measured as the fraction of the time that the sensor node at a participant's house transmitted data to the central database. Data availability was on average 89 % of installed time, with values above 95 % for half of the sensor nodes. This was found to be satisfactory, given that inhabitants were able to occasionally remove power supply, e.g. to use the power outlet for other purposes.

Recruitment of participants for the online survey was done via the same procedure as recruitment of people interested in adopting a sensor node. By the end of the pilot project, 18 inhabitants (5 female, 13 male, age 49 ± 13 yr) had registered in the online system, and they reported sound events and sleep quality with varying degrees of regularity. In total, 210 sound events were reported, and 211 sleep diary records were submitted. Due to this relatively low number of participants, statistical power for drawing significant conclusions from the intake and continuous questionnaires was not always reached during the pilot project. In retrospect, recruitment for the online survey could have been more efficient and targeted, even when the relative low number of inhabitants of the case study area is taken into account. Moreover, although the content of the intake survey was kept short (it could be completed in 10 minutes), this might still have discouraged some potential participants.

4.2   Continuous survey results

The (anonymized) data of the sound event reports and sleep diary records were presented online, together with associated acoustical data and basic indicators calculated for each of these sound events and sleep periods (see Section 3.4). Figure 6 shows a screenshot example of the online sound event presentation interface; a similar system was set up to visualize the results of the sleep diary records in near real-time.

The answers given by the users on the open question within the event report turned out to be very specific. Automatic sound recognition is not going to be able to reach this level of detail for most events reported, although categories of sounds could be compared. Figure 7 (left panel) shows the distribution of the occurrence of reported sound events for broad categories: mechanical sounds (76.2 % of reported events), sounds from nature (11.4 %) and human sounds (12.4 %). The panel also shows the average peak level, measured as L_{A01}, for each of the categories. It becomes clear that the sound level is not the only factor that may cause reporting a sound event; wind and rain sounds are only reported at high levels, whereas animal sounds (e.g. dogs barking) are already reported at low levels. An analysis of the sound event report data for the questions with categoric labels is more straightforward. As an illustration, the reported audibility of sound events was analyzed in terms of a range of acoustical indicators using a multiple regression approach. It was found that the standard deviation of the instantaneous SPL during the period delimiting the sound event explained the largest amount of variance in audibility (although still with a rather low r^2 of 0.088), more than equivalent or maximum levels. Figure 7 (right panel) shows the relationship between reported audibility and the equivalent level and standard deviation of the sound pressure level. A clear although non-linear relationship can be seen. Note that this analysis is based on 1-hour values rather than extremes, which are mainly causing audibility. A more detailed analysis, which delimits the actually reported event, would be necessary to make this link. At the moment of writing of this paper, analysis of the continuous survey result data was still ongoing.

An analysis of the sleep diary records showed that none of the acoustical parameters taken into account shows a clear monotonous influence on the sleep quality. This conclusion also holds when results are analyzed on an individual basis, in order to remove the potential influence of individual differences in average sleep quality. It is therefore expected that the optimal indicator will be a combination of these factors. In addition, shoulder hour noise is a clear indicator for poor sleep quality in some cases. It has to be noted that the sleep diary in this pilot study contained questions on general sleep quality, and was not focused on noise (in contrast to the sound event report which was obviously focused on sound). As noise is only one factor in explaining variation in sleep quality, next to e.g. light pollution, health status etc., it can be expected that a much larger sample size would be necessary to be able to extract statistically significant relationships.

4.3   Basic acoustical indicators

On the basis of the 15-minute aggregate data that is automatically calculated (Section 3.2), diurnal patterns for all basic acoustical indicators can be visualized. As an example, to get a feel of the neighborhood, diurnal patterns of $L_{Aeq,15min}$, L_{A90}, L_{A50}, L_{A10} and L_{A01}, averaged over a 4-month period, are shown in Figure 8 for
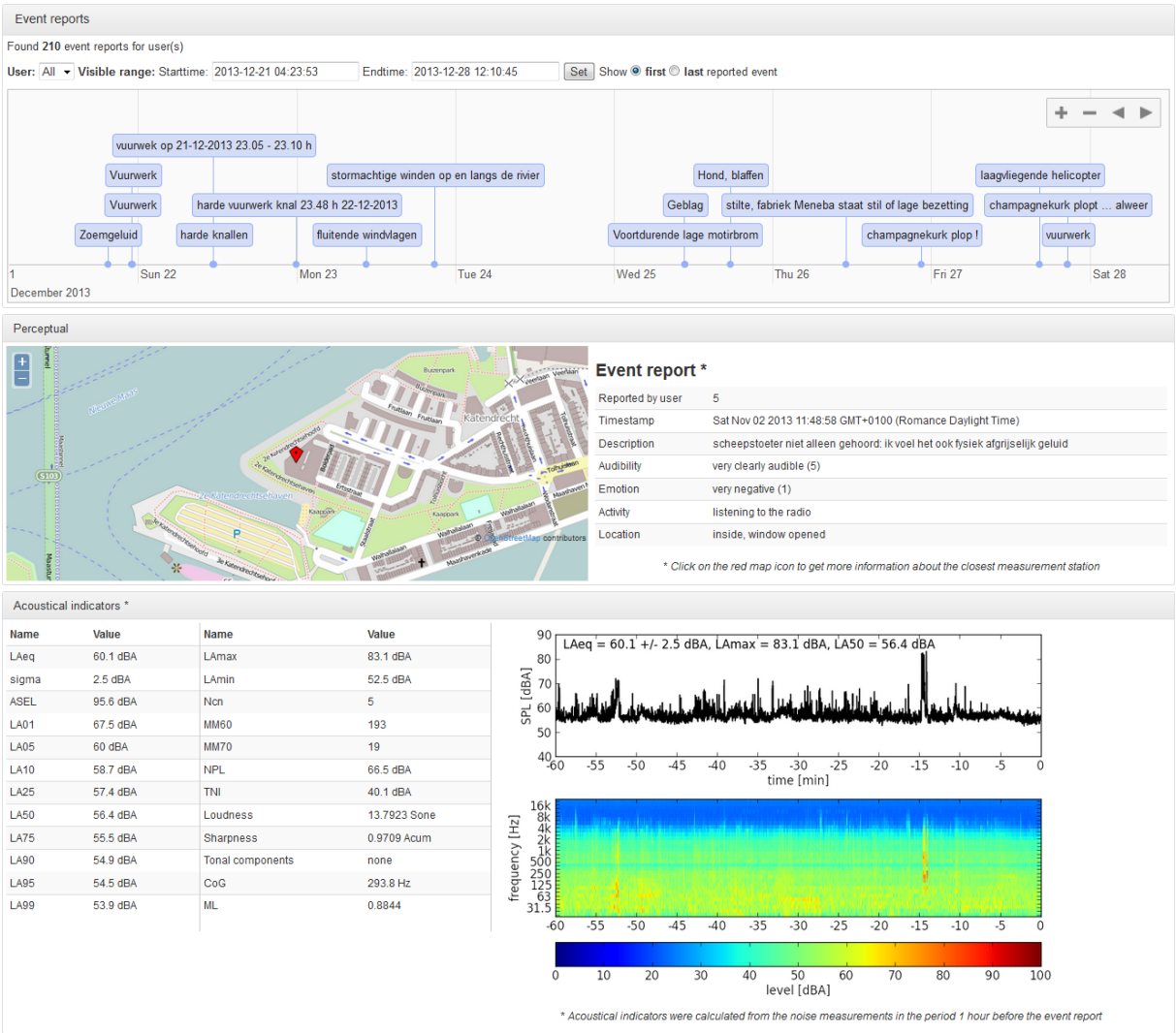
Figure 6 – Online interface for viewing sound event reports. The upper panel shows a timeline with all reported events, the middle panel shows the perceptual attributes of a reported sound event, and the bottom panel shows the acoustical indicators linked to the sound event.
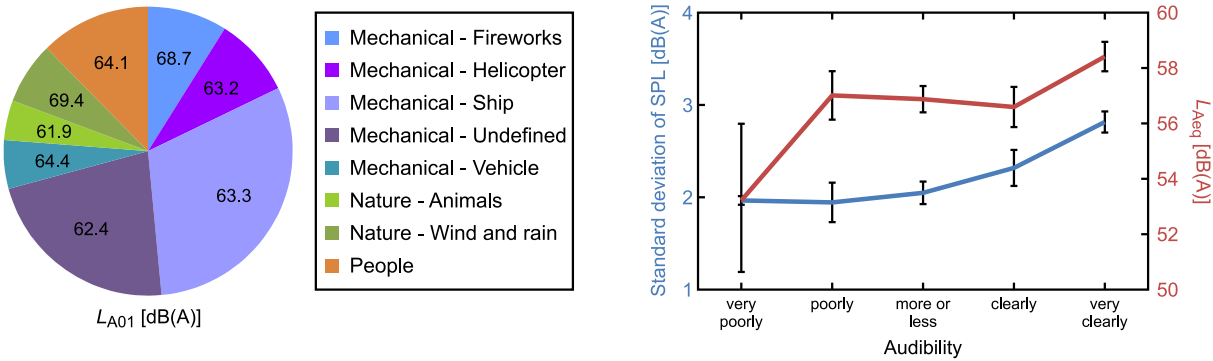

Figure 7 – Left panel: distribution of the occurrence of reported sound events according to general categories, with the average L_{A01} indicated on the diagram. Right panel: relationship between reported audibility of a sound event, and the equivalent level (red curve, right axis) and standard deviation (blue curve, left axis) of the instantaneous sound pressure level during the 1-hour period containing the reported sound event.
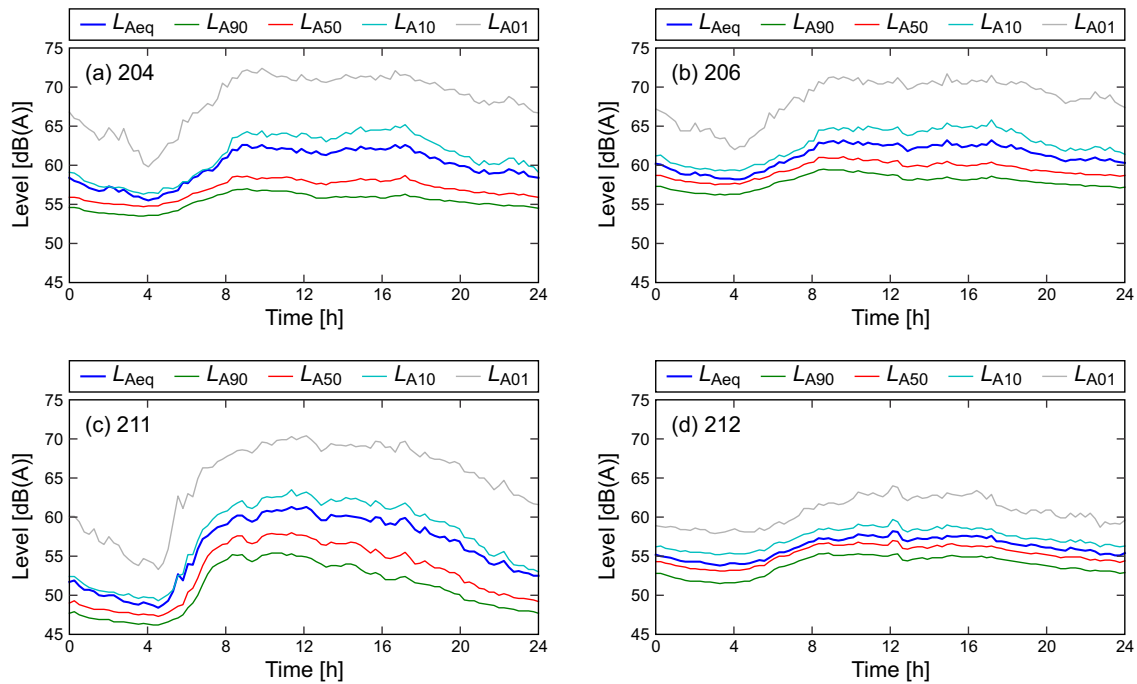
Figure 8 – Diurnal patterns of the 15-minute L_{Aeq} and percentile noise levels (averaged over a 4-month period) for 4 measurement locations.

4 measurement locations inside the study area. In addition, Figure 9 shows diurnal patterns for the number of sound events during 15 minutes, measured in three different ways. The indicators M_{60} and M_{70} count the number of times that the A-weighted instantaneous sound level exceeds the fixed levels of 60 dB(A) and 70 dB(A) respectively; the indicator N_{cn} counts the number of times that the A-weighted instantaneous sound level exceeds L_{A50} with at least 3 dB(A) for at least 3 s, and thus measures sound events emerging from the background. Measurement locations 204 and 206 are both situated along the sounthern edge of the study area, with 206 directly facing a ship (un)loading plant at the other side of the Maashaven. The regular periods of constant noise exposure originating from this plant makes that background levels do not drop below 55 dB(A) for these two locations. Peak levels are due to sound events caused by vehicles passing by on the road along the southern edge. In contrast, for measurement location 211, which is situated at the north side of the peninsula close to the industrial plant, background levels during the night drop to 46 dB(A), but the loading and unloading of trucks during weekdays results in a high dynamic range of the sound level, with a peak of activity before noon. Measurement location 212 is located at the eastern tip of the peninsula, and overall has the smallest dynamic range in sound level, as it is not exposed to any major sound sources directly. It is interesting to notice that values of N_{cn} often have a peak in the late afternoon or early evening, when L_{A50} has dropped, whereas the other sound event indicators do not show this behavior. However, the number of sound events reported within the online survey was too low to draw significant conclusions on which of the event count indicators most closely follows the diurnal distribution of reported events.

4.4   Sound recognition

A model for identifying the sounds that a person would notice while living in the vicinity of each sensor node was deployed (Section 3.2), being initially trained on sounds recorded at different locations in Belgium. Some specific Rotterdam harbor sounds were therefore hard to identify. In order to further train the model, new audio samples were collected in the case study area, and were labeled by humans. Figure 10 shows the percentage of time during the full day (24 h) of November 1, 2013, that specific sounds are likely to be noticed. The collection of sounds is based on the fact that they occurred at least once in any of the points during that day. The label "hum" refers to urban background sound. In node 211, for example, trucks and cars are noticed more often; in node 212, the sounds of people contributes significantly; in node 204, the sound referred to as "engine" has to be interpreted as a mechanical sound, probably originating from a ship unloading.

5.   CONCLUSIONS

The smart sound monitoring pilot study conducted in Katendrecht from August until December 2013 considered environmental sensing as a participatory process. Citizens were encouraged to take part in the study
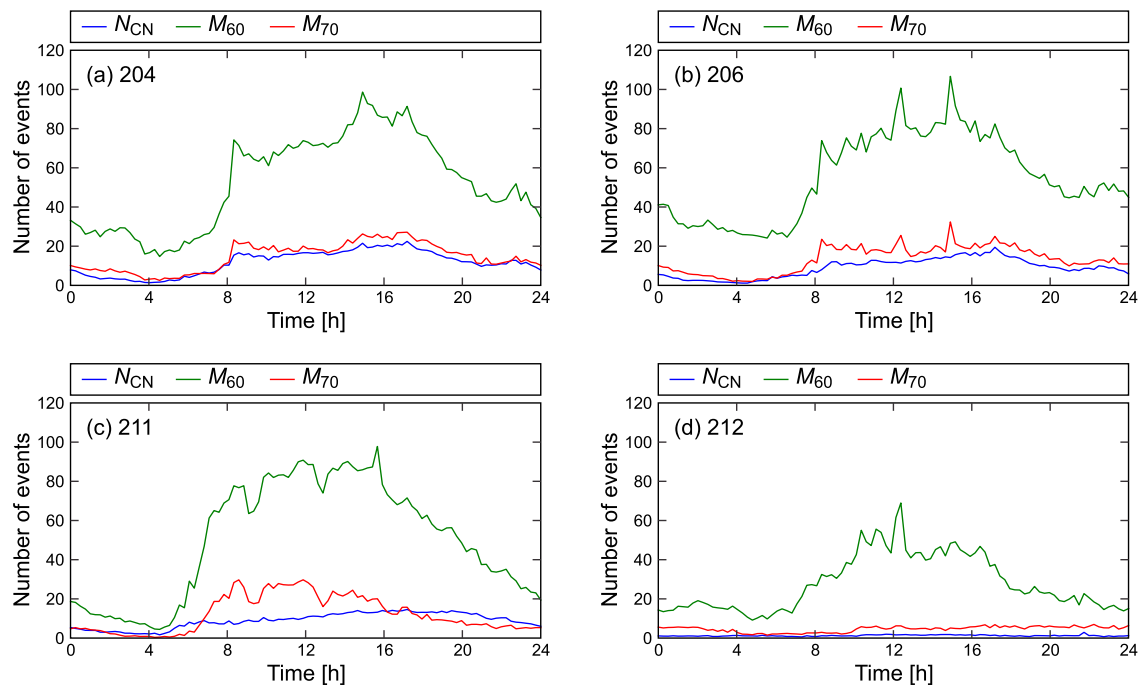
Figure 9 – Diurnal patterns of three 15-minute indicators for the number of noise events (averaged over a 4-month period) for 4 measurement locations.

in two ways: by adopting a sensor node and placing it on their dwelling, and/or by making use of the online survey system to report sound events and their overall sleep quality. The largest challenge of the project turned out to be finding and motivating citizens to take part in the study. The main conclusions that can be taken here are that the threshold should be kept as low as possible, both for hardware installation and online survey participation, that recruitment should be direct and clear, and that participants should have a perspective for a potential improvement of their own living situation. As citizens are directly involved in the data collection process, it may increase policy involvement and nourish environmental awareness as a bonus.

The presented sound measurement system involves intelligent sensor nodes supported by a powerful backend that allows for state-of-the-art acoustical applications. This approach supplements equivalent levels with sound identification, change and event detection, perceptual metadata related to sound events etc. Such data is a valuable source for research and local policy. The coverage of the area with 12 nodes turned out to be quite reasonable, and allowed performing distributed measurement tasks. Furthermore, in contrast to shorter-term *ad hoc* sound measurements, this long-term distributed sensing approach allows to gain more insight into the influence of particular sounds that only occur sporadically. This kind of intelligence opens up new possibilities for implementing a micro noise policy with a focus on the local urban neighborhood scale. Situations that are likely to cause annoyance can be identified in near real-time, which could be very useful if the company or person responsible for the annoyance is willing to act accordingly, after being alerted.

Although the preliminary results of the pilot project regarding the online survey system presented here are less useful for epidemiological research, given the specific study area and the relatively limited number of participants, an extension could still prove to be very useful for this purpose. In order to make sure that a sufficient number of participants engages, additional motivational aspects could be included in the system, such as showing online activity of the participant, or of the participant panel as a whole. In combination with a sufficiently dense network of sensor nodes, this would allow to investigate the influence of the acoustic environment on perception, annoyance, and sleep quality in great detail. For example, the effect of noise exposure during the shoulder hours on sleep quality could be investigated using this approach.

ACKNOWLEDGEMENTS
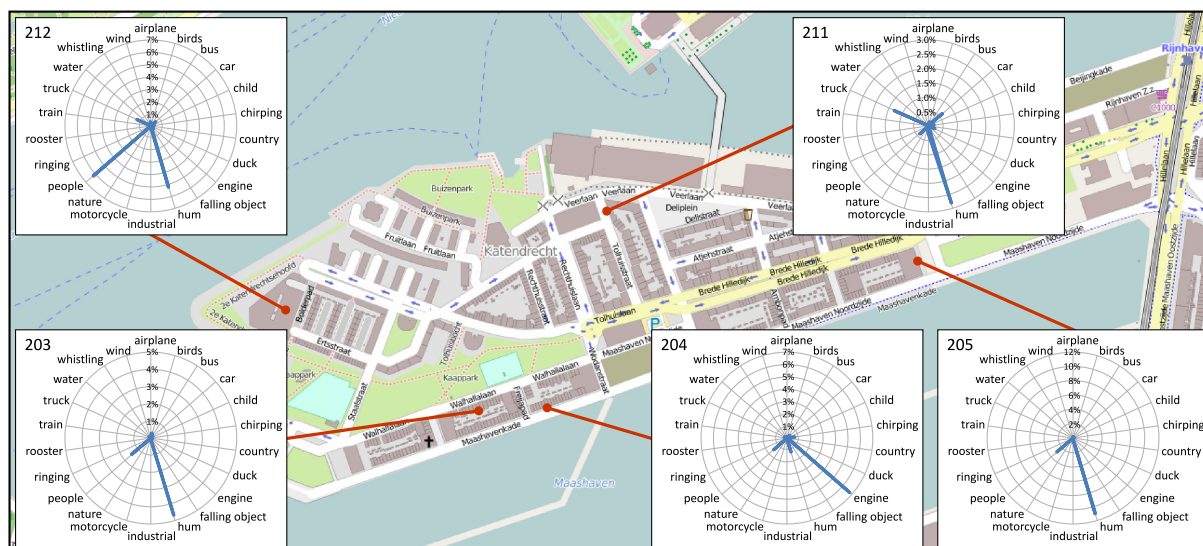
Figure 10 – Percentage of the day (November 1, 2013) that specific sounds are likely to be noticed.

REFERENCES

1. Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise. Brussels, Belgium: European Commission; 2002.

2. Miedema HME, Oudshoorn CGM. Annoyance from Transportation Noise: Relationships with Exposure Metrics DNL and DENL and Their Confidence Intervals. Environ Health Persp. 2001;109(4):409–416.

3. De Coensel B, Botteldooren D, De Muer T, Berglund B, Nilsson ME, Lercher P. A model for the perception of environmental sound based on notice-events. J Acoust Soc Am. 2009;126(2):656–665.

4. Botteldooren D, Lercher P. Soft-computing base analyses of the relationship between annoyance and coping with noise and odor. J Acoust Soc Am. 2004;115(6):2974–2985.

5. Griffiths ID, Langdon FJ. Subjective response to road traffic noise. J Sound Vib. 1968;8(1):16–33.

6. Brown AL, Banerjee D, Tomerini D. Noise events in road traffic and sleep disturbance studies. In: Proc. Inter·noise. New York City, USA; 2012.

7. Aasvang GM, Øverland B, Ursin R, Moum T. A field study of effects of road traffic and railway noise on polysomnographic sleep parameters. J Acoust Soc Am. 2011;129(6):3716–3726.

8. Botteldooren D, De Coensel B, De Muer T. The temporal structure of urban soundscapes. J Sound Vib. 2006;292(1–2):105–123.

9. Oldoni D, De Coensel B, Boes M, Rademaker M, De Baets B, Van Renterghem T, et al. A computational model of auditory attention for use in soundscape research. J Acoust Soc Am. 2013;134(1):852–861.

10. Boes M, Oldoni D, De Coensel B, Botteldooren D. A biologically inspired recurrent neural network for sound source recognition incorporating auditory attention. In: Proc. IEEE IJCNN'13. Dallas, Texas, USA; 2013. p. 596–603.

11. Veenstra P, van den Berg F. Onderzoek naar klachten over laagfrequent geluid in Groningen. Technical Report NWU-108. Groningen, The Netherlands: Natuurkundewinkel, University of Groningen; 2002.

12. Meijman TF, de Vries-Griever AH, de Vries G. The evaluation of the Groningen Sleep Quality Scale. Heymans Bulletin HB 88-13-EX. Groningen, The Netherlands: University of Groningen; 1988.

13. Kishikawa H, Matsui T, Uchiyama I, Miyakawa M, Hiramatsu K, Stansfeld SA. The development of Weinstein's noise sensitivity scale. Noise Health. 2006;8(33):154–160.

14. Cummins RA, Eckersley R, Pallant J, van Vugt J, Misajon R. Developing a national index of subjective wellbeing: the Australian Unity Wellbeing Index. Soc Indic Res. 2003;64(2):159–190.