AN EXPLORATORY REVIEW OF SOUNDSCAPE DESCRIPTOR MODELS FOR SOUNDSCAPE ASSESSMENT AND DESIGN PRACTICE

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1 INTRODUCTION

With focus on human perception, soundscape has attracted attention from multidisciplinary studies and soundscape design/management is believed to be a powerful and innovative tool to prevent and improve noisy environments. [1,2,3]The first ISO standard of soundscape concept was published in 2014, and then followed by another two ISO standards on data collection and data analysis in 2018 and 2019, respectively (ISO 12913-1, ISO 12913-2, ISO 12913-3).[4,5,6] In the UK, an emphasis on the importance of appropriate soundscape in good design and planning firstly appears in PPW10 at the level of national policy (Planning Policy Wales - Edition 10).[7] It also shows a strong tendency of soundscape practice in the UK and across the EU.[8,9] It is believed that soundscape service will be emerging in industry in several years based on these evidences. However, there have been no clear guidelines on how to assess soundscapes and optimise soundscape design in practice. There is also a need for the development of soundscape tools in order to standardise and efficiently conduct soundscape assessment, as well as to predict the outcome of soundscapes of design scenarios in the early design stage.

A number of studies have aimed to propose general descriptors for “soundscape quality” with multiple indicators, rather than using single soundscape components or properties.[10,11,12] The descriptors measure the perception of the characteristics of the acoustic environment, assessing whether a soundscape is good or bad. For instance, the descriptors can be annoyance, pleasantness, quietness or tranquillity, restrictiveness, and vibrancy etc.[13-17] The indicators can be the acoustic indices (e.g. L_{10}, L_{90}),[18-20] psychoacoustics (e.g. loudness, sharpness)[15,21,22], visual factors (e.g. people and natural view) [10,23], meaning of sounds (e.g. human voice, music and birdsong)[19,24], as well as perceived properties (e.g. perceived loudness and liveliness)[18]. The indicators are used in the descriptor modelling as variables. The models can be linear or non-linear.[25-29] The models indicate the relationships between the perceived soundscape characteristics and the physical and/or the perceived properties of the acoustic environment, which have taken the aural-visual interaction, psychological factors and social factors into account.[30-33] Among the models, those with only physical properties (no perception data needed) can be used to predict how people perceive the acoustic environment without the costly and time-consuming laborious task of asking people about their perceptions. With the predictive model, the underlying causes of the perceived properties can be estimated. Therefore, accurate models can be the adapted in the design, aiming to bridge the gap between the soundscape research outcome and design practice.[10]

Soundscape mapping, the visualisation of the soundscape quality in a 2D map, have been developed with the scoring of diverse descriptors, in both macro and meso scales in the academic domain.[56,64,65] However, since soundscape assessment is really context-based, no widely-used guidelines or techniques for soundscape descriptor modelling or soundscape mapping have been proposed. There has been no systematic review, either. What soundscape descriptor models the researchers have developed? What indicators have been employed? Is it possible to use merely physical properties as indicators to calculate the descriptor scores? Are there any models that can be suggested for the practical assessment of soundscape in certain contexts?

Therefore, soundscape descriptor modelling will be systematically reviewed in this paper to explore the up-to-date soundscape models and the possibility of application of soundscape models in soundscape mapping.

2 REVIEW OF SOUNDSCAPE DESCRIPTOR MODELLING

An extensive review of the studies on soundscape descriptor modelling (since 2000) has been conducted to explore how the models have been developed and what are the significant indicators for different descriptors. Table 1 shows the descriptors, acoustic indicators, other indicators and contexts of the soundscape descriptor models.

Table 1 The soundscape descriptor models as reviewed.

Descriptors*	Acoustic/Psychoacoustic indicators	Other Indicators	Contexts	Number of references
Annoyance	• L_{Aeq};[13,25,26,27,45,51,61] • L_{eq};[46,50] • Day-night noise level (DNL); [28,32,52,62] • Nighttime noise level;[49,63] • Day–evening–night Noise level L_{den};[33,49,62,63] • Noise level (Different definitions of noise level were used in the different cities);[53] • Tonal component appearance (TC) **, spectral level deviation (SLD), temporal sound level variance (TSLV), percentage of sound level (PSP) in these critical frequency bands, crest factor (CF)***;[46] • Total loudness calculated every 2 ms and exceeded 10% of the time (**N_{10}**);[45] • $TETC_{13-18}$, N_{1-12}*****;[45] • L_{A50}, L_{Ceq} - L_{Aeq} [19]	• Type of dwelling;[13] • Overall Quality of Life, Self-rated health, Physical quality of life, Psychological quality of life, Social quality of life, Environmental quality of life;[31] • Noise Sensitivity; [25,28,32,45,49,50,53] • Windows oriented toward the street, Noise annoyance at workplace, Heavy vehicles at night-time, Duration of stay at apartment at day;[49,50] • Gender, age and education;[25,28,32,50,63] • Type of the water sound (stream sound or fountain sound), Threshold****;[25] • Audibility of natural and technological sounds;[19] • Distance to the roads, degree of urbanization, reported traffic density, household size;[28] Community tolerance level[52]	• Environment exposed to road traffic noise;[19,27,28,50] • The vicinity of an airport;[31,45,52,53] • Urban street;[49] • Environment exposed to road traffic and railway noise;[13,46] • Combined aircraft, road traffic, and railways noise environment;[32,62] • Leisure, work and home (exposed and non-exposed based on road traffic noise);[63] • Industrial and road traffic combined noise environment;[26,33] • Combined water sound and road traffic noise environment;[25,51] • City park and green space;[19] • Combined construction noise environments[61]	• (20)
Pleasantness	• L_{A50}, L_{A10}, L_{A90};[18] • $L_{50,\ 1kHz}$, the normalized Time and Frequency Second Derivative (TFSD)******;[54] • L_{eq}, L_{Aeq};[15] • N_{10};[12] • Sharpness, Loudness, Roughness;[15,22] • The amplitude of the spectral peak, the frequency value of the spectral peak, Spectral energy (3–16 kHz), Judged pitch, Judged energy variation[22]	• Silence, Visual pleasantness, Liveliness, Time ratio of presence of light vehicles, Envelopment;[11] • Overall Loudness, time of presence of sound sources of traffic (T), voices (V), birds (B);[54] • Soundscape dominated by technological/natural/human sounds dichotomous variable coded [0, 1];[12] • Percentage of perceived sound sources (human sounds, traffic noise), visual quality;[24]	• Multiple urban outdoor spaces;[12,15,18] • Near and in urban parks;[11] • Urban paths;[54] • Street, market, shopping mall, and park;[22] Commercial area, residential area, CBD area and recreational area;[24]	(7)

Overall quality	• L_{A50}, L_{Ceq}-L_{Aeq}, L_{10}-L_{90}, L_{10}, L_{90};[16,19] • Intensity of sound level (e.g. L_{Aeq}, L_{AFmax}, L_{AFmin}, L_{10}, L_{50} and L_{90});[55]	• Audibility of natural sounds and technological sounds;[19] • Overall loudness, road traffic, • visual amenity, voices;[18] • Perceived dominance of sound source types (i.e. traffic, human, water, bird);[56] • The presence of events and the assessment of the positive or negative perception of the types of sound sources existing in the area;[55]	• Multiple urban outdoor spaces;[18,55,56] • Urban parks and green areas;[16,19]	(5)
Tranquillity	• L_{Amax}, L_{Aeq};[23,57,58] • L_{day};[59] • L_{A50}[60]	• Proportion of natural features % (NF); [23,57] • Natural and Contextual Features (NCF), Minor adjustments or moderating factors (MF);[58,59] • Pleasantness, non-fitting sounds, Noise event count (Ncn), Music-likeness (ML1), biological/nature/landscape value[60]	• Outdoor open spaces (urban and nature); [23,57,58] • Parks and gardens with traffic noise;[59] • Rural area[60]	(5)
Vibrancy	• Loudness (N), Loudness Variability (N_{10}-N_{90}), Roughness (R), Fluctuation Strength (Fls);[10,22] • The amplitude of the spectral peak, Judged pitch, Judged energy variation[22]	• Presence of Music, Presence of People[10]	• Multiple public urban space[10,22]	(2)

*Note: one reference may include more than one model descriptor.
** The effect of a tonal component depends on its central frequency, its level, the total spectral character and level of the noise.[66]
***The crest factor (CF) measures the impulsiveness of the sound pressure level within the 10-min stimuli, and is defined as the ratio between the maximum sound pressure and the RMS value of the sound pressure.[46]
****Threshold takes the value of 1 when WSNR is equal to 0-3dB and the global SPL is lower than or equal to 70 dBA, otherwise 0. WSNR is the difference in sound pressure level between water source and road traffic. A negative WSNR value denotes that the SPL of road traffic is higher than that of water source, and vice versa.[25]
*****sum of the maximal (across time) level of tonal components in critical bands) within critical bands from 13 to 18 Barks (denoted as $TETC_{13\text{-}18}$ and used to characterize tonal components in high frequencies; while N_{1-12} characterizes the perceived intensity at low and medium frequencies.[45]
******TFSD represents the time and frequency normalized deviations of each recorded sample. It aims to describe the frequent time variations within specific frequency bands, which are characteristic of tonal or harmonic sounds such as voices or birds.[54]

In the search of the soundscape descriptor models, it was found that a number of studies focused on the modelling of Annoyance and Pleasantness. The contexts of the Annoyance models are mostly traffic noise environments, while the contexts of Pleasantness models cover more diverse urban spaces, e.g. urban parks, market and park; commercial area, as shown in Table 1. Models of overall soundscape quality were also developed in a few studies, measuring whether a soundscape is 'good' or 'bad'. Besides the former three descriptors, there are two more significant descriptors, i.e. Tranquillity and Vibrancy.

Tranquillity is representative of the positive effect of the sound environment in place.[34] Less stress is experienced when the tranquillity and pleasantness perceived in the place are greater.[34] In landscape and urban design, tranquillity is defined in terms of absence of anthropocentric influences, such as urban development, traffic, noise intrusion and man-made structures. Examples of definitions in which tranquillity is related to the engagement with nature and to the absence of human intrusion include 'a state of calm and quietude associated with peace, considered to be a significant asset of landscape'[35] and 'the quality of calm experienced in places with mainly natural features and activities, free from disturbance from manmade ones'[36]. A more comprehensive definition of tranquillity is given by both Welsh Government[37] and Natural Resources Wales[38,39] as "An untroubled state, which is peaceful, calm and free from unwanted disturbances. This can refer to a state of mind or a particular environment". Tranquillity has been mentioned or is required in a set of the UK policies, such as The Rural White Paper, Our Countryside: The Future – A fair deal for rural England[40], National Planning Policy Framework[41], Scottish Natural Heritage Landscape Policy Statement 2005 (Scotland)[42] and CAP1616[43].

Although the studies in Vibrancy models are limited, Vibrancy is a vital soundscape descriptor associated with preferred health and safety outcomes in urban areas.[10] Soundscape vibrancy refers to two auditory aspects: organisation of sounds and changes over time.[44] Aletta and Kang (2018) conducted interviews to define and understand the concept of vibrancy and concluded that vibrancy is related to a pleasantness dimension, which indicates positive feelings and gets people in a state of excitement.[10] Unlike quietness and tranquillity, vibrancy is more appropriate to represent soundscape quality of pleasant and eventful places, such as an urban square or plaza.

The following summarises the review of the models for each descriptor, including Annoyance, Pleasantness, Overall quality, Vibrancy and Tranquillity, as shown in Table 1.

1.1 Annoyance

Overall noise level is mainly considered in Annoyance models, rather than tonal components of the sounds. Among the Annoyance models, L_{Aeq} is the most frequently used acoustic indicators, followed by Day-night noise level and Day-evening-night noise level. Psychoacoustic indicators are rarely used, except for the study by Gille et al (2017), which included loudness N_{10} as one of the variables.[45] A set of indicators for tonal components were used as variables in the study on relationship between noise annoyance and overall indoor sound exposure.[46] The indicators for the components of low frequencies (e. g. $N_{1—12}$, L_{Ceq} - L_{Aeq}) were analysed in very few studies[19,45], although annoyance of low-frequency noise has attracted a lot of attention[47,48].

Noise sensitivity and demographic characteristics (i.e. gender and age) are frequently used as a non-acoustic variable in Annoyance models (see Table 1), which indicates the significant effects of individual differences on annoyance judgement. Visual stimuli was hardly considered as variable in the models, except for one indicator "Windows oriented toward the street" which are mentioned in two studies[49,50]. Recognition and differentiation of sound sources were also emphasized in the studies on road traffic noise environment and city parks and green areas[19,25], of which the positive effects of the natural sounds were considered. In one study of road traffic noise annoyance by Botteldooren et al (2003), the geographic information was also analysed and presented as non-acoustic indicators in the models.[28] Indicators with regard social factors (e.g. Social quality of life) were included in the Annoyance models when investigating aircraft noise annoyance in the vicinity of airports.[31]

Road traffic noise annoyance was most commonly studied and modelled. Combined road traffic noise environments with other sound sources also attracted much attention, as shown in Table 1. Among the studies, only water sounds were used as positive natural sounds presented in the models.[25,51] A considerable number of studies focussed on aircraft noise annoyance.[31,45,52,53]

1.2 Pleasantness

Psychoacoustic parameters play an important role in Pleasantness models.[12,15,22] L_{A50} is more often used in Pleasantness models than Annoyance models. The sounds were analysed at the level of specific frequency bands.[22,54] The perception of different sound sources is emphasized in the models in terms of dominance and time-ratio.[11,12,24,54] For instance, Aumond et al (2017) used the non-acoustic indicator "time of presence of sound sources of traffic, voices and birds" in Pleasantness models in the context of urban paths.[54] Visual quality is also considered in Pleasantness models.[11,24] Some other perceived factors have high relevance with Pleasantness too, such as liveliness and overall loudness.[11]

Compared with Annoyance models, the contexts of Pleasantness models are more diverse. The contexts cover different urban outdoor functional spaces, e.g. parks, markets, commercial areas, residential areas, public transport stations and recreational areas.[11,15,22]

1.3 Overall quality

L_{A50} is the most frequently-used acoustic indicator in Overall quality models, followed by L_{10} and L_{90}.[16,19,55] The indicator for the components of low frequencies, L_{Ceq} - L_{Aeq}, was also demonstrated to be relevant to the overall quality of soundscape.[19] The audibility and perception of sound sources are considered essential non-acoustic factors in most of the Overall quality models reviewed.[18,19,55,56] Visual quality was used as a variable in one of the models.[18] Similar to Pleasantness models, the contexts of Overall quality models also cover various urban outdoor spaces, including urban parks and green areas, as shown in Table 1.

1.4 Tranquillity and Vibrancy

Pheasant and Watts published a set of research results on tranquillity models for both urban spaces and rural areas, and visual stimuli, i.e. the view of natural features, was used as a criteria in these Tranquillity model.[23,57-59] L_{Aeq} was considered to be an appropriate acoustic indicator in most of the models, while De Coensel and Botteldooren (2006) suggested L_{A50} as the most important acoustic indicator in the assessment of quiet rural soundscape quality.[60] Non-fitting sounds and Noise event count are two variables relating to noise intrusion and unwanted disturbance[60], which correlates with the concepts of tranquillity.

Soundscape Vibrancy is important for vibrant environment creation in urban public spaces, beyond noise control. Psychoacoustic parameters play the most vital roles in the Vibrancy models than any other descriptor models.[10,22] N_{10} is used in Annoyance, Pleasantness and Vibrancy models, as shown in Table 1. No acoustic indicators were suggested as model variables within the studies reviewed. In the study by Aletta and Kang (2018), presence of people and music were also demonstrated to have high relevance with regard to Vibrancy.[10]

3 TOWARDS SOUNDSCAPE QUALITY MAPPING

There are no universal models that can be applied to soundscape assessment in all the contexts based on the review above. Some indicators in the descriptor models were tailor-made for the certain studies and impossible to be obtained with limited resources (e.g. sound analysis software) in soundscape practice. Therefore, the models for the descriptors with widely-used acoustic indicators and easily-calculated indicators in the previous studies were explored, aiming at the soundscape quality mapping. The models can be applied in practice when the soundscape contexts are the same or similar, for instance, traffic noise environment, urban parks and combined traffic and industrial noise environment.

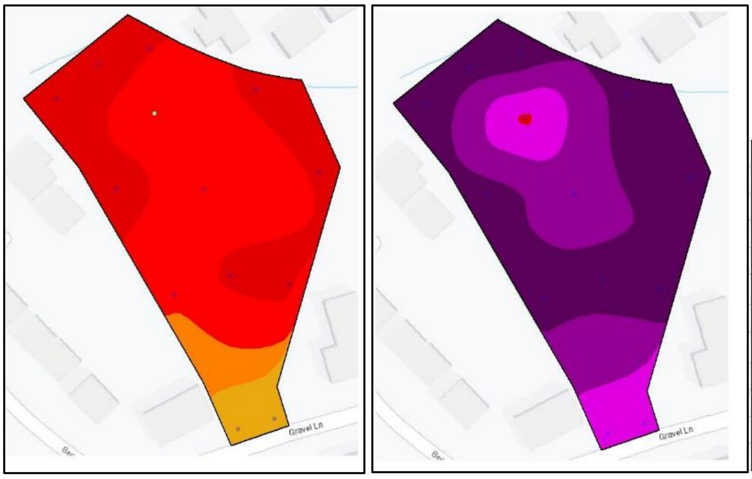
For soundscape quality mapping, two steps were conducted, i.e. calculation of the soundscape descriptor values and visualization of the values in 2D maps. A workbook was created as the soundscape descriptor calculation tool with the models selected from the relatively high-quality previous studies, of which the outcomes show relatively large numbers of participants in the soundscape data collection, high goodness of fit of models, and published in high-quality peer-reviewed journals in recent years (after 2005). The workbook includes input sheets, calculation and outputs. The indicators of the models are widely-used or easy to be calculated. The references of the models were clearly stated under the structure of Annex A Minimum reporting requirements in ISO/TS 12913-2, showing the detailed contexts of each model.

A pilot practice of soundscape mapping has been undertaken by the Acoustics and Vibration Team at Bureau Veritas in the spring of 2020. The soundscape data were collected during the daytime on the 23rd March 2020 shortly before the national COVID-19 pandemic lockdown was imposed using grids of 10m by 10m, which is the same as the mapping resolution.

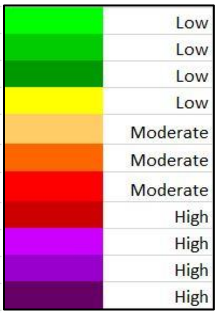
The site used for the pilot scheme was a local green area space designated a community garden situated in a suburban area of Cheshire measuring approximately 0.7 Hectares (see Figure 1). The site is surrounded by detached domestic dwellings and is bordered largely by hedgerows and trees with the dominant noise source been a road to the south of the site as can be seen in the image below and birdsong within the surrounding vegetation.

Presented below are the details of the pilot soundscape maps generated for the two descriptors, Tranquillity and Pleasantness (see Figure 2). During the sound monitoring at each grid point the sound climate in the area was considered representative of normal conditions with no extraneous noise sources affecting the measurements. During the measurements the climatic conditions were dry with wind speeds of <1m/s.

Figure 1. Community Garden used for Pilot Soundscape Mapping Scheme



Scores	Rating
0	Low
1	Low
2	Low
3	low
4	moderate
5	moderate
6	moderate
7	high
8	high
9	high
10	high



Tranquillity **Pleasantness**

Figure 2. Tranquillity map and Pleasantness map with key to colour coding of maps for each descriptor.

4 CONCLUSIONS

This paper presents the findings of a systematic literature review conducted to explore the significant indicators and regression models in soundscape descriptor modelling research, and suggests a practical soundscape mapping method based on the review.

Overall sound level LAeq is the most frequently used acoustic indicator in Annoyance models, while it is far less commonly used in other descriptor models. The indicators relating to the tonal components of sounds were rarely analysed in Annoyance models, but they were more often analysed in Pleasantness and Overall quality models. Psychoacoustic indicators play a vital role in Pleasantness and Vibrancy models, while they are rarely used in Annoyance, Overall quality and Tranquillity models.

It is interesting to note that Noise Sensitivity and demographic characteristics are frequently used as a non-acoustic variable in Annoyance models, while they were rarely mentioned in the other descriptor models. Visual stimuli was hardly considered as a variable in Annoyance, Overall quality or Vibrancy models, but it was widely used in Pleasantness and Tranquillity models. The perception of different sound sources was emphasized in the models of all the descriptors reviewed, especially Overall quality models.

Whilst Annoyance models were most commonly associated with road traffic noise environments, the models of all the other descriptors have rather diverse outdoor spaces as contexts.

A practical soundscape mapping methodology has been developed based on the finding of the literature review, and a pilot study has been conducted to show the application of the methodology. More work will be done to compare and optimise the design scenarios by the results of soundscape mapping in the future.

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