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10 Questions

Ten questions concerning computational urban acoustics

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ABSTRACT

The sound environment in urban areas is complex, as caused by many sources of sound and influenced by a variety of acoustic propagation effects. In order to combat noise and create acoustic environments of high quality, it is of utmost importance to be able to predict the time dependent sound field in such areas. Engineering methods are useful for a fast analysis and noise mapping purposes, but remain tools with limitations. Besides, computational modelling of urban acoustics, i.e. the group of wave-based solution methods, has obtained its role for complex environments as well as for research purposes. These computational models have become more mature in the recent decade. This paper addresses questions that are of interest for all scientists and research-oriented engineers in this field, as well as researchers in related fields of urban physics. The questions relate to the need for computational methods, the relevance of including various urban propagation effects in computational modelling, and to the preferable computational methods and approaches to use. Answers are based on scientific work by the author and many other urban acoustic researchers, and will also contain visionary opinions of the author.

1. Introduction

1.1. Sound in the urban environment

In urban areas, various environmental aspects affect human well being and health, as temperature, humidity, wind, rainfall, direct sunlight, air pollution and noise. These aspects are influenced by many factors, as meteorological conditions, the urban topology, materialisation of buildings, vegetation and traffic flows. As regards environmental noise, i.e. unwanted sounds mainly caused by road traffic, rail traffic, airports and industrial sites, health impacts are a growing concern among both the general public and policy-makers in Europe [1]. Among environmental stressors that impact public health, environmental noise has been ranked second in six European cities [1]. Also, the trend is that noise exposure is increasing in Europe compared to other stressors, which are declining [1]. The number of noise sources are high in urban areas, leading to noise levels much higher than in rural areas. For various health effects, WHO has quantified the impact of environmental noise in disability-adjusted life-years (DALYs) in European Union Member States and other western European countries [1]. Together, at least 1,5 million healthy life years are lost every year from environmental noise in the western part of Europe.

The European noise policy to reduce environmental noise translates into two tracks. At one hand, specific noise emission limits are imposed for most road vehicles and for many types of outdoor equipment in order to control noise pollution. At the other hand, there is the European Noise Directive (END), which focuses on a common approach to address environmental noise. The END consists of monitoring the noise situation by producing noise maps of major roads, railways and airports and of major agglomerations (> 100,000 inhabitants for the 2012 noise map), on a 5-year basis. The noise maps contain yearly averaged L_{den} and L_{night} values. Based on the noise maps, END requires that action plans should be made. Fig. 1 shows a part of the Amsterdam noise map.

Urban noise can be related to adverse health effects. However, other sounds than environmental noise are present in the urban environment too, and environmental noise does not necessarily dominate the urban sound environment [3]. As a consequence, the urban sound environment is not just a matter of being noisy or not. It can, for example, be expressed as measured in a metric space along dimensions such as pleasant-unpleasant, exciting-boring, eventful-uneventful and chaotic-tranquil [4]. A recent focus in the research arena of the urban sound environment focuses towards soundscaping, which can be considered as the perception of the time-dependent sounds in the urban environment.

While environmental noise is addressed by EU legislation and scientists have identified soundscaping as a mechanism to design urban environments of high acoustic quality, the role of acoustics in

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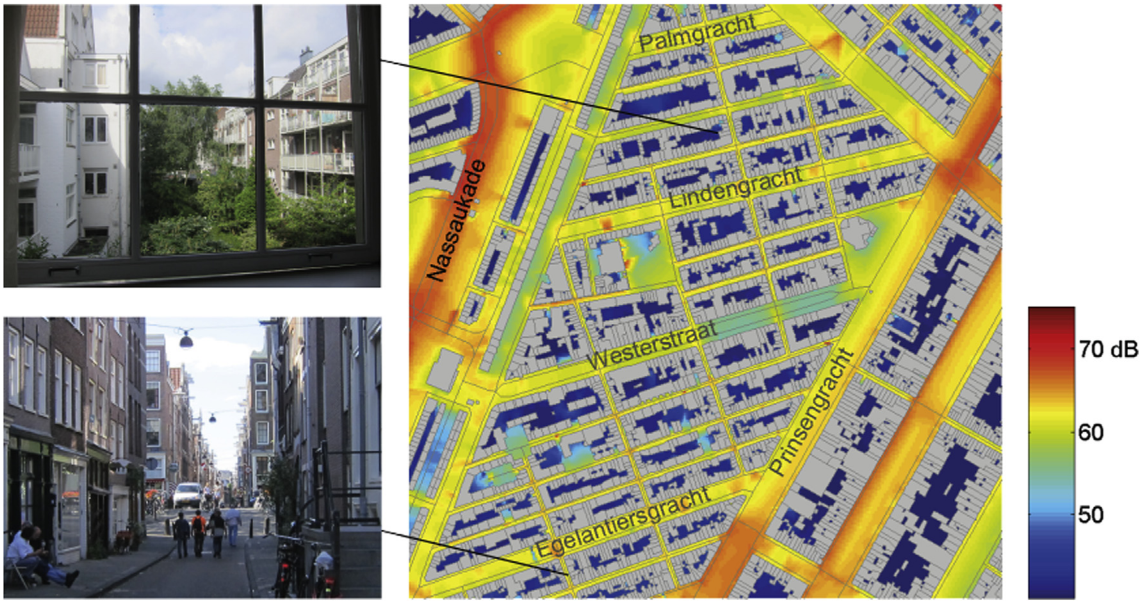

Fig. 1. Part of the Amsterdam noise map for traffic from the Qside project [2]. There are busy streets (orange), less busy streets (yellow), quiet courtyards (blue) enclosed by houses (grey). The less busy streets, illustrated by the lower photograph, are typical of this lively urban area (Jordaan area). The upper photograph shows a view from a quiet façade on a quiet courtyard. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the planning for urban areas is still marginal. A recent EU project demonstrates good practice of involving acousticians in the planning process, and shows that in-depth acoustic knowledge on prediction methods, noise control and soundscaping is needed for this purpose [5]. As such, an important shift is needed in the planning processes, where acousticians get a more prominent position such that excessive noise levels can be prevented and environments of high quality can be ensured.

Following from the text above, methods to predict urban sound propagation are important for the following reasons:

- Spatial sound levels: This is important for noise mapping purposes according to the END (indirect estimation of health effects), but also in the context of planning and design of urban environments;
- Impact of noise control measures: The noise reduction effect of measures taken in noise action plans needs to be quantified by predictions. Also, research and innovation in noise control measures is supported by these methods;
- Auralization: This is the process of making acoustic environments audible in a virtual reality sense. For this purpose, methods predicting the time dependent sound field to synthesize sound signals in urban areas are needed. For perceptual evaluation of an urban soundscape in psychophysical research or in real-life applications, auralization is important. Moreover, auralization is a powerful tool in communicating the consequences of an acoustic scenario (e.g. proposed noise reduction measures) to planners, architects and citizens, as it offers the possibility to virtually experience environments.

1.2. Urban propagation effects and urban scales

The spatial (and time) dependent sound pressure levels in urban areas depend at one hand on the actual sound sources, and at the other hand on the propagation of sound from these sources in the environment (i.e. the acoustics of the environment). Important properties of sources in the built environment are their sound power, spectral characteristics and directionality. Whereas quantification of properties of sources in the urban environment can be found elsewhere [6,7], this paper focuses on sound propagation between source(s) and receiver(s) in the urban environment. Urban sound propagation is influenced by the following fundamental aspects: sound reflection with surfaces (e.g. ground surface, building façades, roofs, barriers), diffraction from edges as from noise barriers and building roofs, scattering from rough surfaces as irregular façades and atmospheric turbulence, refraction by temperature and wind gradients in the atmosphere, and attenuation of sound waves by air absorption, see Fig. 2. All these aspects influence sound pressure levels, but it is important to understand that only the damping mechanisms (through acoustic absorption of boundary materials and air absorption) will lead to lowered sound levels on a larger scale.

As regards the planning and design of urban areas with respect to acoustics, a macroscale and microscale can be distinguished. At microscale, the effect of individual buildings and surfaces are important. A typical microscale is the sound field within a street or at a square. For a street environment, important aspects are the width and height of the street, the degree of façade irregularities and its absorption properties, and the percentage of openings in the façades (e.g. by cross streets). Urban quiet sides and quiet façades play an important role in urban environments. According to END, quiet sides are areas to which Member States have set maximum L_{den} values, typically courtyards and larger urban parks. A quiet façade is the façade of a dwelling with L_{den} more than 20 dB lower than at the façade having the highest value of L_{den} [8]. According to the END, action plans should also aim to protect these quiet areas against an increase of noise. Aspects at microscale that influence the quiet sides are the shape and properties of the roof of buildings bordering a quiet side, as well as the dimensions and materialisation of the quiet side. Distant traffic can also contribute to sound pressure levels in quiet sides, and meteorological conditions are important in that case [9].

At macroscale, the average level of the sound pressure level over a larger area is of interest, and urban aspects that influence this are the floor space index, ground space index, population density,

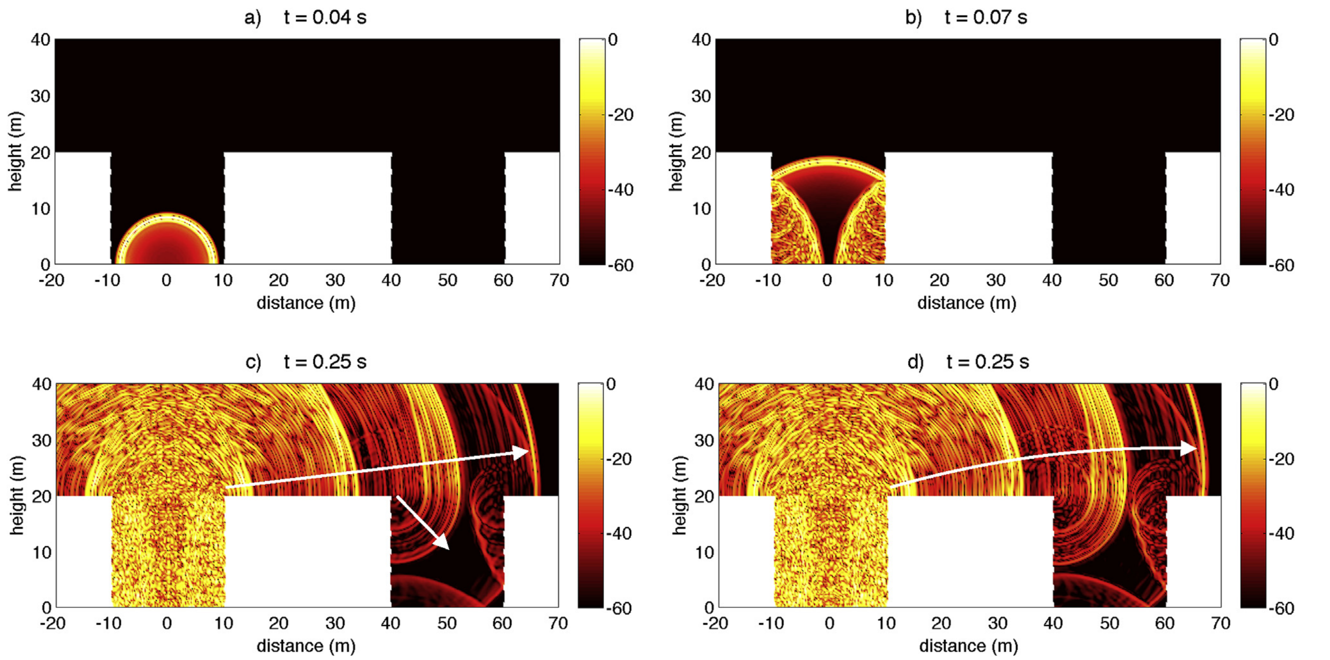

Fig. 2. Snapshots of wave propagation in a section of two streets computed by the pseudospectral time-domain method [31], with levels expressed in dB relative to the maximum sound pressure level. Sound is exited by a pulse in the left canyon. a) Direct sound wave is visible, b) Sound is reflected by façades. Due to the depressed windows, the reflected sound field is partly scattered, c) Sound is diffracted into the nearby street canyon (lower arrow). d) as c) but for propagation through a mean atmospheric wind speed profile with wind direction from left to right. The sound waves are bent downwards, indicated by the curved arrow.

building area/lot area ratio, compactness index, ratio of open space, complexity of the perimeter index and road coverage, building coverage and accessible space coverage [10–15].

The focus of this paper is at the microscale.

1.3. Computational urban acoustics approaches

Various methods have been developed for predicting the sound field in urban areas at microscale. In acoustics, a separation is made between geometrical acoustics (GA) based methods, diffuse field methods and wave-based methods. In this paper, computational urban acoustics refers to the wave-based methods, which predict urban acoustics with high accuracy. Besides, GA methods are referred to as engineering methods, the methods typically used for noise mapping purposes.

In GA methods, sound waves are regarded as rays that interact with boundaries. For GA methods to be applicable, boundary surfaces typically need to be larger than the wavelength of the modelled frequency, making these models mostly appropriate in the high frequency range. Whereas wave-based methods implicitly include all phenomena of wave propagation in their solution, GA models are an explicit composition of the interaction of sound rays with boundaries, i.e. as reflection, diffraction and scattering. GA models have been developed for the purpose of noise mapping, and the first models date back from the 60ties (see Ref. [16] for an overview). Although noise maps are produced over areas ranging to tenths or even hundreds of square kilometres, the maps can have a resolution at microscale level (i.e. smaller than typical street dimensions, see Fig. 1). GA models are suitable for noise mapping purposes, as they enable to compute noise maps in reasonable calculation time and within reasonable accuracy of about 3 dB for many cases [17], but excluding inner city environments among these cases. Many GA models have been developed for noise mapping purposes, see Refs. [18,19] for an overview. In order to harmonize a GA model used for noise mapping in Europe, the common prediction method CNOSSOS has been developed, a methodology operational for the next round of strategic noise mapping in the European Union, foreseen for 2017 [20]. Diffuse field methods are applicable when the environment is similar to an indoor space (as in inner city environments) and the sound field is spatially smooth [21]. Diffuse field methods as the diffusion equation method [21] have been developed for streets (diffusion equation methods use a volumetric grid in which the sound energy is propagated instead of the ray-like approach common to GA methods, see references in Ref. [22]). These methods enable to generate rapid predictions of the sound field in those environments, in contrast to GA methods that get slower when many façade reflections are to be included, see Sect. 2.1.

Wave-based methods solve the governing physical equations. The equations in the time domain including meteorological effects are the linearized Euler equations (LEE)

$$\begin{aligned} \frac{\partial \boldsymbol{u}}{\partial t} &= -(\boldsymbol{u}_0\cdot\nabla)\boldsymbol{u} - (\boldsymbol{u}\cdot\nabla)\boldsymbol{u}_0 - \frac{1}{\rho_0}\nabla p, \\ \frac{\partial p}{\partial t} &= -\boldsymbol{u}_0\cdot\nabla p - \rho_0 c^2 \nabla\cdot\boldsymbol{u}, \end{aligned} \tag{1}$$

or the wave equation when excluding meteorological effects[1]

$$\Delta p - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}p = 0. \tag{2}$$

In the frequency domain, the Helmholtz equation can be solved,

$$\Delta p + k^2 p = 0, \tag{3}$$

with c the adiabatic speed of sound, ρ_0 the atmospheric density, $\boldsymbol{u}_0$

[1] By utilizing the effective sound speed approach, meteorological effects could be included using the wave equation and Helmholtz equation, see e.g. Ref. [23].

the wind velocity vector, $\boldsymbol{u}$ and p the acoustic velocity and pressure respectively, and k the wave number. When all input in a wave-based method is appropriate, i.e. source location and properties, geometrical data of urban topology, material properties and meteorological conditions, the methods should be able to reproduce sound propagation with a high accuracy. The major limitation of wave-base methods is their computational overhead, which increases with the highest frequency to be solved. Driven by the advances in computer power, wave-based modelling has received increased attention in recent years [24]. Wave-based methods have been applied to solve sound propagation in urban streets, cross-streets, squares and to courtyards. A variety of methods have been proposed [25–35], generally with high accuracy for the cases envisaged, but with varying computational costs. Wave-based propagation methods are also used to quantify the contribution of noise to courtyards from distance sources [9,36], and simplified expressions have been derived for that purpose [37–40]. A challenge in wave-based methods is to reduce computational costs but keep accuracy, such that problems of moderate size are feasible to solve. The scope of computational urban acoustics methods is to

- Act as reference methods for validation or improvement of GA methods (e.g. as in Refs. [38,40]);
- Investigate fundamental effects on urban sound propagation as turbulent scattering [27] and the role of diffuse boundaries [41];
- Predict sound fields in spatial or frequency areas where GA methods fail, as in evaluation of noise abatement measures [42,43]. This might give rise to hybrid prediction methods [41,44];
- Act as input model for auralization, although this is an application currently being explored, see also Sect. 2.2.

1.4. Predictions versus measurements

As in other fields of physics, experimental results are indispensable to ensure the quality of predictions. As for urban acoustics, measurements are predominantly taken to validate or calibrate predictions, and it is good practice that developed prediction methods are compared with measured data. Alternatively, benchmark cases [45,46] are available for mutually comparing prediction models. The validation of prediction models for urban acoustics can be divided into measurements to validate a part of a model, and measurements to compare with the application of the model in a full urban setting. To the first category belong, i) measurements to determine the surface impedance of outdoor materials (see for an overview [47]), ii) measurements to validate the effect of meteorological conditions as turbulence [48] and mean wind and temperature fields [49,50] in simplified configurations, iii) measurements to identify the effect of interferences in street canyons [51] and iv) measurements of diffraction around a noise barrier edge [16]. These measurements are carried out in the field, but also scale model measurements are commonly used as circumstances can be well conditioned [16,27,51–53]. Field measurements in urban areas provide the opportunity to determine the quantities (L_{den} and L_{night}) needed for creating noise maps. The validation of prediction methods with such measurement data is vital in order to rely on the prediction methods.

The costs of sensors to measure sound pressure levels are reducing and with the increasing power to process data, it becomes more feasible to get real-time noise maps from actual measurements. However, for END noise mapping, the data from sensors is too scarce to generate complete noise maps and prediction methods are needed for this purpose. A hybrid approach is interesting in this respect, where measurements and predictions are coupled to generate real-time noise maps [54].

1.5. Structure of the paper

The remainder of this paper is as follows. In Sect. 2, the ten questions on computational urban acoustics are raised and answered. First, a brief answer is given, followed by a more extensive answer. In these questions, the author elaborates on the role of computational urban acoustics methods, as well as on how such methods need to be used. The questions are ordered according to the following thematic structure:

- The need for computational modelling (Q1,Q2);
- Physical aspects for modelling (Q3,Q4,Q5);
- Computational aspects of modelling (Q6,Q7,Q8);
- Future visions (Q9,Q10).

Note that the scope of the questions relate to inner city environments at microscale. It is important to remark that many research contributions in the field of computational urban acoustics are written by European based authors, which partly confines the typical studied urban configurations: whereas non-European cities often are characterized by high-rise buildings, European city centers often consist of (semi-) enclosed low-rise building blocks. In Sect. 3, the ten questions and answers are summarized.

2. Ten questions (and answers) on computational urban acoustics

2.1. Question 1: What are the limitations of engineering methods in urban sound prediction?

Answer Engineering methods typically have problems in areas with multiple reflections – in particular for low frequencies and in areas shielded from direct noise exposure such as cross streets and courtyards – for irregular façade surfaces, as well as to account for complex meteorological effects.

Engineering methods for prediction of urban acoustics have developed over the years [18], and among them the Harmonoise method has likely the highest accuracy [20,55]. In urban environments where sound propagates by multiple reflections with façades, Harmonoise (and other engineering methods) needs to include many façade reflections in order to predict accurate results [56]. As these methods rely on point-to-point (source-to-receiver) calculations and every reflection with a boundary implies another (image) source, such calculations imply a high computational overhead. Also, as reflected sound waves are added incoherently, actual phase effects are not included, which in cases of modal aspects in streets can lead to incorrect predictions [51]. This is primarily the case for the low frequency range, where the modal behaviour dominates. On top of that, façades typically have irregular surfaces as from window depressions and balconies, which are not accounted for by these models. Such reflections play an important role in the sound field of city street canyons and squares [17,57,58] and need to be accounted for. Beside streets, the accurate prediction of sound levels in cross streets is of concern. For such locations (see the yellow-coloured narrow streets in Fig. 1), the direct transmission from source positions to a receiver location are mostly intersected, implying that the sound field is composed of many reflections. Including a limited number of such reflections would, also here, underestimate the actual sound levels.

Similar to the multiple reflections, multiple diffracted sound fields need to be computed in some cases, as for example sound propagation to areas shielded from road traffic as courtyards.

Including too few diffraction contributions (in combination with reflections) will underestimate sound pressure levels, e.g. see Refs. [25,56,59]. Computational methods have been used to improve the prediction of engineering methods at quiet sides, and simplified expressions have been proposed [37,38]. Harmonoise assumes locally reacting surface impedance values, which leads to inaccurate results when impedances cannot be treated as locally reacting. Fig. 3 shows an example of the absorption coefficient computed for a grass ground surface, with a locally reacting approach and the correct (extended reacting) approach, indicating the possibly occurring errors. Many outdoor surfaces as this surface can be treated as locally reacting surfaces, and the error using the locally reacting approach in the Harmonoise method is therefore not significant for most cases. Other engineering methods do not use impedance values but approximate values to take into account absorption from interaction with surfaces.

As regards meteorological effects, engineering methods include the effect of turbulent scattering and effects of mean wind and temperature profiles. However, the latter rely on statistical average profiles [20] or linear profiles [55]. Both cases are simplifications, and in particular not valid when the meteorological wind and temperature profiles are non-linear and not constant in the domain as due to obstacles [55].

Concluding, engineering methods work well for scenarios where not too many façade reflections need to be included, and when meteorological conditions can be simplified. Generally, current engineering methods for noise mapping purposes might lead to a too optimistic picture of the urban noise situation.

2.2. Question 2: Are wave-based methods needed for realistic auralization?

Answer This is still not clear, but it can be argued that for low frequency sounds as from public transport buses and lorries in narrow city streets, wave-based methods are needed.

Despite the zoo of methods available to predict sound levels at the urban microscale, see Sect. 2.6, surprisingly little attention has been paid to the authenticity quality of auralization from these methods [60]. Auralization of urban scenarios has primarily focussed on source modelling, e.g. in Refs. [61,62], simplified scenarios as pass-by cases over a ground surface and in the presence of a noise barrier or other noise control measures [63]. Auralization of sounds in inner city environments has less been encountered [64,65]. Such environments resemble indoor environments, for which recent developments are to predict the spatiotemporal sound fields from wave-based methods in the low-frequency part, and GA methods in the high frequency part [66–69]. Wave-based methods are not used for the high frequencies – apart from being computationally costly in frequency range as mentioned in Sect. 2.8 – because the sound field for those frequencies is in nature rather diffuse, i.e. interference effects are less relevant and the field is smooth in space and in the frequency response. As predicting the sound field in streets by engineering methods is inaccurate, in particular for low frequencies (see subsection 2.1), the research question whether this frequency part should for auralization purposes be modelled by a wave-based model is currently being studied. Further questions relate to the time-dependent crossover frequency between wave-based and GA methods in a hybrid wave-based/GA approach, which obviously depends on the type of environment and sound source(s) to model. Also, the level of detail of the boundaries to be modelled is not known yet. According to [70], the required level of detail of the boundaries is in the order of magnitude of roughly half a meter for an indoor application, but evidence for this statement should be increased and no outdoor application is yet considered.

An important final note is that sounds that are to be auralized in the urban environment typically differ from sounds in indoor environments: auralization in urban environments often involves sound from traffic whereas auralization of indoor environments is often related to speech or music signals.

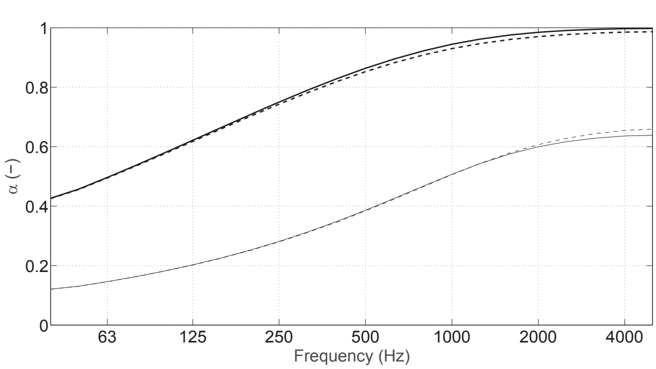

Fig. 3. Absorption coefficient of an outdoor surface (grass ground) according to Figure C2 of Ref [23] with flow resistivity $\sigma = 200$ k Pa s/m^2. (Solid Thick) 80° angle of incident sound wave to surface, extended reacting surface, (Dashed Thick) 80° angle of incident sound wave to surface, locally reacting surface, (Solid Thin) 40° angle of incident sound wave to surface, extended reacting surface, (Dashed Thin) 40° angle of incident sound wave to surface, locally reacting surface.

2.3. Question 3: How important are the acoustical properties of surfaces in the calculations?

Answer Whereas the ground effect is crucial for suburban and rural environments, the impedance and irregularities of vertical surfaces as façades influence the spatial and temporal sound field in urban areas, and are more important for increasing distance between source and receiver, and when the line-of-sight between source and receiver is interrupted.

Two main surface properties can be distinguished, the surface impedance Z (if a surface may be assumed to be locally reacting) and geometrical surface irregularities. The surface impedance Z is related to the acoustical absorption coefficient α (i.e. the fraction of the incident acoustic intensity that is absorbed). The impedance describes the reaction of the surface to an incident sound wave and modifies the reflected sound wave both in amplitude and phase. The range of impedance values of outdoor materials is large. However, the impedance of typical vertical surfaces of barriers and façades – i.e. brickwork, stucco, glazing, concrete, steel – is high, and absorption coefficient are below 0.3 for the frequency range of interest for most materials [71]. At the other hand, porous materials as soil may have absorption coefficients close to 1 for some frequencies. As sound waves are reflected multiple times by façades in inner city environments, the impact of the impedance values of vertical surfaces is large.

As regards surface irregularities, these affect sound in different ways depending on the frequency of sound. For frequencies with wavelength(s) much larger than the typical dimension of the irregularities, surfaces reflect the wave as it would be flat, see Fig. 4. For wavelengths in the order of the irregularity scales, the sound wave is diffusely reflected. For wavelengths smaller than the irregularities, the reflection is specular again (with respect the local surface plane, for example due to balconies [72]). However, irregularities already influence the sound field for dimensions smaller than the wavelength: due to the effect of multiple reflections, the diffuse part of a multiple reflected sound wave is dominating over

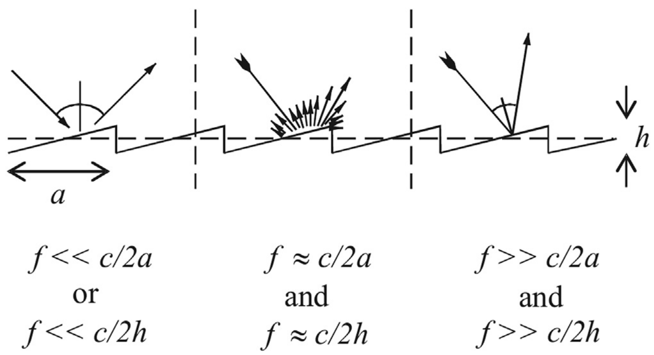

Fig. 4. Frequency ranges for scattering from a periodic surface of repetition distance a, and roughness depth h [81].

the specular reflected part even if the diffuse reflected part for a single reflection is small [3]. This is demonstrated in Fig. 5.

The effect of the surface impedance and irregularities depends on the location of the receiver with respect to the source. Mainly three scenarios can be distinguished in inner city environments, with increasing importance of surface properties. 1) A line of sight is present between source and receiver and their distance is small. The direct sound wave then dominates the level at the receiver, and the impact of reflections with vertical surfaces is not very large (Fig. 6(a)). 2) A line of sight is present between source and receiver and the distance is large, the influence of the reflections gets more important compared to the direct sound wave [53] (Fig. 6(b)). 3) No line-of-sight is present between source and receiver, for example for receivers located in a courtyard, and the properties of materials get highly important [73] (Fig. 6(c,d)). Fig. 6 shows the impulse responses (i.e. the response of the environment to an impulse generated at the source position, measured at the receiver position) for four configurations. Every 'spike' represents a reflection with a façade. It is obvious that the contribution from the façade reflections increases for the second and third scenario. The effect of different impedance values in a street has been quantified in Refs. [3,53,57,74–76], and on squares in Ref. [58]. For non line-of-sight locations, the effects of absorption are quantified in Refs. [25,41,77]. In a street, Kang found that about 6 dB can be reduced by changing absorption coefficient α from 0.1 to 0.9 [57]. For an increase of the α from 0.05 to 0.5, Hornikx found a reduction of about 4 dB for a 40 m source-receiver separation in the same street, while the reduction is lower for the receiver close to the source (about 2 dB) [3]. The reduction is about 15 dB in the adjacent courtyard, with a lower spatial dependency. Note that more moderate effects are to be expected when the increase of absorption cannot be achieved, as when the baseline absorption values are higher [77,78].

As regards diffusion, completely diffuse boundaries were computed to reduce the sound pressure levels about 8 dB at a 60 m source-receiver separation in the same street, while due to back-diffusion, increased diffusion leads to higher levels close to the source [74]. The effect in the courtyard can be about 10 dB [25,41], for a lower degree of diffusiveness. Also here, if surfaces have baseline diffusion the effect of changing the surface is smaller. Besides influencing the sound level, the reverberation time is reduced for increasing α values and diffusiveness of surfaces. An exception are short source-receiver distances, where diffuse façades lead to a higher reverberation time.

Finally, the two discussed effects have a different impact for different width to height ratios of a street [79,80].

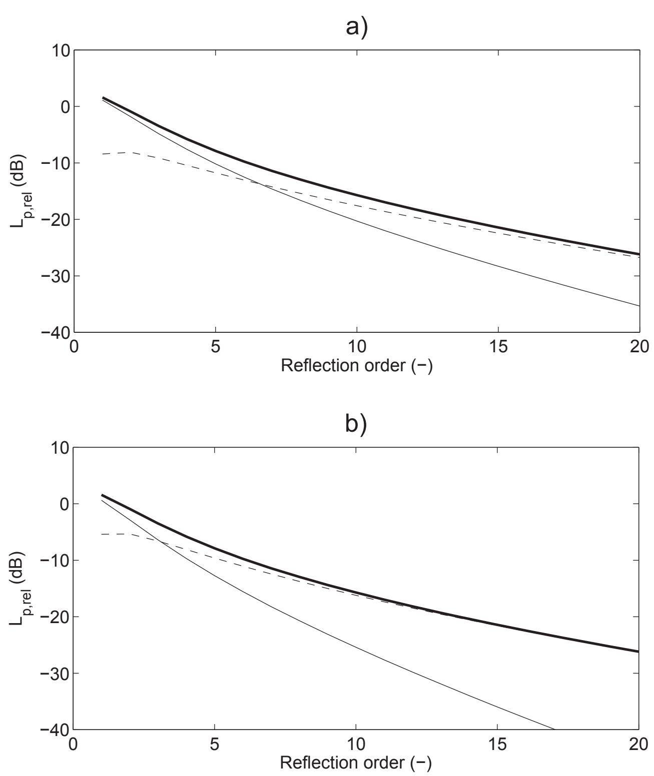

Fig. 5. Effect of diffuse reflecting boundaries for scenario of sound source and receiver in the middle of a 20 m wide street canyon, 40 m apart. Absorption coefficient of façades is equal to 0.1 and results are calculated with a ray method. (Solid Thick) Total sound pressure level per facade reflection contribution relative to direct sound pressure level, (Solid Thin) Sound pressure level from specular reflection components, (Dashed Thin) Sound pressure level from diffuse reflection components. a) scattering coefficient façades equal to 0.1, b) scattering coefficient façades equal to 0.2.

2.4. Question 4: Should bulky vegetation as trees be included in predictions?

Answer The effect of vegetation is more significant with denser types of vegetation, leads to scattering and absorption of sound, and should therefore be included.

Vegetation in urban areas has a range of ecological advantages, as listed in Ref. [42]. Recently, vegetation as noise reducing possibility in inner city environments, in particular building envelope greening measures, have been identified as well [82–87]. Also, there is growing evidence that visibility of vegetation by itself affects noise perception positively [88–93]. For inner city environments, vegetation types that can be considered are low-height noise barriers, vegetated façades, vegetated roofs and trees. Low-height vegetated noise barriers (i.e. 1 m) were shown to be useful in road traffic noise applications at street level, see Fig. 7. This has been assessed by calculations with different numerical methods [94]. These devices can be placed close to the driving lanes, thereby yielding road traffic noise reduction of about 5 dB(A). The most important absorption mechanism of low-height noise barriers is the green-wall substrate at its surface. Without vegetation (i.e. a rigid surface), the reduction is only about 1 dB(A).

The potential of green roofs in decreasing the intensity of wave propagation over buildings has been originally identified by numerical work presented in the Refs. [82,83], and subsequently by in-situ [85] and laboratory measurements [86]. The porous substrate of a green roof is expected to be responsible for the main effect, although it has been shown that the interaction between the substratum and the growing vegetation can influence the

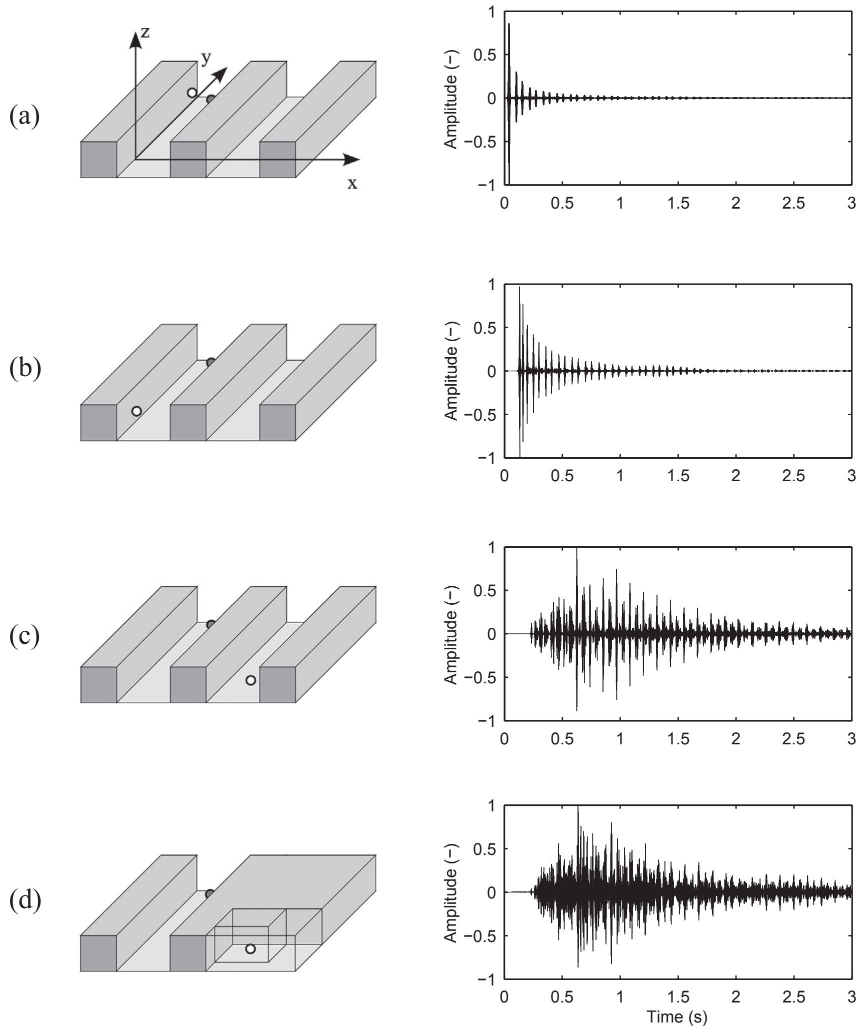

Fig. 6. Calculated 250 Hz octave band impulse responses with the pseudospectral time-domain method [31]. Amplitudes are normalised to the maximum amplitude per subplot. Sound source at (9 m, 40 m, 0 m) and flat façades with small absorption coefficient ($\alpha = 5$ %). (a) Canyons situation, receiver position (0 m, 40 m, 5 m); (b) Canyons situation, receiver position (0 m, 0 m, 5 m); (c) Canyons situation, receiver position (49 m, 0 m, 0 m). (d). Canyon-courtyard situation, receiver position (49 m, 0 m, 0 m).

Fig. 7. Low height vegetated barrier along a road with head-and-torso simulator behind the barrier for acoustic recordings [103].

absorption [95,96]. In particular, the increase in the absorption coefficient of a soil-plant system is pronounced in the case of high-density, low-porosity soils. The effect of vegetated roofs depends on the roof shape, and a maximum effect of 7.5 dB(A) noise reduction for propagation over a roof has been found [42]. Green-wall systems, usually consisting of highly porous and low-weight materials placed in a confinement system, are useful sound absorbers [84,97]. In contrast, common building skins are rigid or close to being rigid. The effect of green-wall systems is larger for roadside courtyards than for trafficked streets (see Sect. 2.3) and may amount up to 4 dB(A). An interesting application of vegetated surfaces are openings to courtyards, greening those surfaces has shown to amount to 4–5 dB(A) reduced sound pressure levels in the courtyard [98].

A tree can acoustically be considered as a volume of small elements scattering and partly absorbing sound waves. At frequencies above 1 kHz, trees contribute to sound attenuation increasingly with frequency due to sound scattering by trunks and branches, as well as foliage scattering and absorption by viscous friction and damped vibrations [99]. A study has been conducted on the scattering and absorption effects of a single tree [99,100]. Scattering showed not be dependent on foliage of the tree, but presence of leaves shows increased absorption at high frequencies (above 2 kHz). Further work is still needed to characterise the effect of other factors such as leaf size, leaf shape and thickness, but also the distribution of biomass in the crown. The effect of trees in streets has been studied to a small extend only [100,101], and indicates to lead to slightly larger values in the street (due to backscattering) and lower values in roadside courtyard for high frequencies. Research is ongoing to the effect of the tree crown in street canyons [102].

2.5. Question 5: Are meteorological effects relevant to include in predicting urban sound propagation?

Answer For line-of-sight propagation within streets meteorology is less relevant, for propagation over rooftops effects may be large.

As for meteorological effects, scattering from atmospheric turbulence, refraction by mean wind or temperature profiles, as well as air absorption can be distinguished. While meteorological effects on outdoor sound propagation over flat terrain, undulating terrain or in the presence of a noise barrier has been studied substantially [23,104], the investigation of the meteorological influence of sound propagation in and over urban areas including the effect of the urban morphology is numerically rather unexplored so far [9,105]. Both the meteorological fields (wind and temperature) as the acoustic propagation is more complex for such cases. Recently, with the development of numerical methods, some research has appeared [9,36,106,107]. Generally, the mean wind and temperature values and turbulent intensity levels are rather low below the rooftop level. Also, since the effect of refraction increases with propagation distance and line of sight distances between source and receiver are usually not large in inner cities, meteorological effects on street level are small [107]. However, studies on meteorological effects inside streets are rare, and effects have not been well quantified [52]. Above roof levels though, the turbulent intensity as well as the gradients of the mean wind and temperature profiles can be strong. Turbulence above roof level has shown to have a substantial effect on the scattering of sound into the non-directly noise exposed side of buildings [39,94], and it has been shown that meteorological effects are needed to predict levels at such quiet sides [38]. Atmospheric turbulence also leads to a strong variation in sound pressure levels [94], which is important to include for auralization. For distant propagation, a large effect has been quantified due to mean wind profiles of more than 10 dB [9,36], and moderate effects for shorter distances [107]. Air absorption increases with distance and (roughly also) with frequency [23], and becomes important for distant propagation as well. The challenge on quantifying meteorological effects on urban sound propagation is to obtain reliable and detailed meteorological data, either from measurements or from CFD calculations, and couple those to a computational urban acoustics propagation method. This is of interest both for short-term prediction of levels (e.g. from outdoor concerts) and for long term levels for noise mapping purposes.

2.6. Question 6: What computational method is most appropriate to compute urban sound propagation at microscale?

Answer Although there is no single answer, methods that do include a priori knowledge of the exact solution (as the Green's function in BEM) as well as time-domain models deem to be more appropriate.

Computational methods for urban sound propagation at microscale have been developed over the last two decades with purposes as outlined in Sect. 1.3. The methods should be capable of including the following aspects:

- Meteorological effects as refraction by mean wind and temperature fields, scattering by atmospheric turbulence and air absorption. The spatially dependent atmospheric field variables should be included;
- Reflecting surfaces as the ground surface and building façades with their frequency-dependent impedances. Reflections can be partly diffuse, and multiple reflections as in urban street canyons should be included. Surfaces may moreover be curved or oblique;
- Multiple diffractions near vertical and horizontal edges. The roof type of buildings, which often has a complicated shape, was shown to be important with respect to the shielding of noise in this respect [108];
- Frequency range. The frequency range of importance is mostly related to traffic noise, i.e. up to 1.6 kHz for positions shielded from direct exposure to noise [108]. The frequency range for auralization purposes is not known yet (see Sect. 2.2), as hybrid

Table 1
Level of appropriateness of computational urban acoustics methods regarding prediction of urban sound at microscale: (−) low, (o) medium or (+) high.

Method	Type[a]	Meteo			Reflection		Diffraction	Frequency	
		Mean profiles	Turbulence	Air Abs.	Geometry	Materials		Storage[b]	Acceleration[c]
PSTD [31,32,111,112]	TD	+	+	+	o[d]	-[e]	+	+	+
FDTD [27,106,113]	TD	+	+	o[f]	o[d]	+	+	o[g]	+
BEM [28,114]	FD	-[h]	-[h]	o[i]	+	o[j]	+	o[g]	o[i]
FM BEM [29]	FD	-[i]	-[i]	o[i]	+	o[j]	+	+	o[i]
ESM [25,26]	FD	-[h]	-[h]	+	o[d]	o[j]	+	o[g]	o[i]
TLM [33,115–117]	TD	+	+	+	o[d]	+	+	o[g]	+
PE [34,35]	FD	+	+	o	-[h]	o[j]	o[k]	o[g]	o[i]
modal/FEM [30]	FD	o[i]	o[i]	o[i]	-[h]	o[j]	+	o[g]	o[i]

[a] Time domain method (TD) or Frequency domain method (FD).
[b] Storage refers to the needed storage capacity of the method.
[c] Acceleration through parallel implementation on CPUs and/or GPUs.
[d] Staircase approximation.
[e] Frequency independent boundary conditions.
[f] Classical attenuation only.
[g] Large number of grid points, see Table 2.
[h] Simplified approaches only.
[i] Although this should be possible, it has not been encountered for urban acoustics applications.
[j] Locally reacting surface impedance.
[k] Kirchhoff approximation.

approaches might imply that only the low frequency part needs be modelled by a wave-based method.

The methods that have been developed for computational urban acoustics at microscale, with their strengths and weaknesses, are listed in Table 1. More computational methods have been developed for detailed prediction of (outdoor) sound propagation than listed in the table, as FFP [23], DWM [109] and LBM [110], but these methods have not been applied to urban acoustics at microscale.

From Table 1, it can be seen that for the accurate line-of-sight prediction of the sound field inside streets (i.e. excluding the qualification for meteorological conditions), many computational approaches apply (o or +). In particular, FDTD, (FM)BEM, ESM and TLM give accurate results for typical boundary conditions. PE and modal/FEM have some geometrical limitations, and PSTD is limited by its boundary conditions that are frequency independent. When the computational storage overhead is important, PSTD is in favour, as well as the FM BEM method, as those methods implicitly include a priori knowledge of the exact solution.

For receiver locations in geometrically shielded positions, meteorological conditions are important. For those predictions, FDTD, PSTD, PE and TLM are in favour as they are domain discretization methods, in contrast to methods like ESM and BEM that discretise (parts) of the boundary only and including moving inhomogeneous effects in the Green's function is complex, see references in Ref. [3]. As is clear from the rightmost column of Table 1, a recent development in computational urban acoustics is the acceleration of codes by (partly) implementing the code on the graphic processing unit (GPU), [32,117,118]. These accelerations increase the feasibility to compute wave fields (at higher frequencies) in a shorter time.

Finally, for auralization purposes, time-domain (TD) methods are preferred as computed impulse responses can then rather straightforwardly be used. Frequency domain (FD) solutions can be used as well for auralization, as the time signals are obtained after applying an inverse Fourier transform to the FD results. However, a fine FD resolution is needed then. Air absorption can be applied as a postprocessing step in a TD method (for example by make use of wavelets [16]), whereas in an FD method, it should be included in the equations if no inverse transform to the time domain is made. In case of refraction, the travel distance of waves is not that obvious and air absorption should be included in the equations, both for FD as TD methods.

2.7. Question 7: When is a full 3D computational method needed?

Answer 3D methods are needed when the modelled urban geometry cannot be considered as invariant in one direction, for which the problem cannot be composed out of a 2D solution(s).

As for other fields of physics, for computational efficiency reasons it is favourable to reduce the dimensionality of acoustic solutions when possible. For urban acoustics at microscale, the following applies:

- 2D solutions: For some cases the sound field in a 2D section of the full problem is similar to the solution of the full problem, in particular when the problem is invariant in one direction which is called a 2.5 D geometry such as the insertion loss of a thin barrier [119]. Examples are point-to-point cases in a canyon section [25,41] see Fig. 6(a), and point-to-point calculation in a horizontal section of an urban situation [120,121];
- 2.5D solutions: For point-to-point calculations in non-perpendicular cross sections of 2.5D configurations as in Fig. 6(b,c), a 2.5D solution can be applied [26]. This implies that the full 3D solution can be obtained by only making use of 2D calculations and applying a Fourier-like transform. Also, the 'twisted' approach has been shown to be a valuable simplification for non-perpendicular cross sections in 2.5D configurations [82], i.e. replacing the 2.5D case by a 2D section including source and receiver location.
- 3D solutions: These are needed when the geometry cannot be considered as 2.5D, examples can be found in Refs. [77,107,122,123], and in Fig. 6(d).

A 2D point-to-point calculation actually implies that the solution of a coherent line source is computed. Road traffic can be considered as a line of sources, but these sources are incoherent. A traffic line source solution can thus be obtained by modelling multiple point sources incoherently. Therefore, it is important to convert 2D solutions to get 3D point-to-point solutions by correcting for the difference in geometrical spreading between the two methods. This conversion is easily applicable to a time-domain solution, i.e. a multiplication of the 2D solution by $\frac{1}{\sqrt{ct}}$ with c the sound speed and t the travel time. Note that for an inhomogeneous or moving medium due to meteorological conditions, this conversion is not straightforward as the speed of sound is not homogeneous.

2.8. Question 8: Are 6 points per wavelength enough for computational urban acoustics?

Answer The 'six points per wavelength' rule of thumb in computational acoustics applies for some computational techniques in urban acoustics, but can be higher or lower depending on the used technique.

All computational urban acoustics methods spatially discretise the computational domain, either a volumetric discretization (as in FDTD, PSTD and TLM) or a boundary discretization (BEM, ESM) is applied. Numerically solving the governing physical equations (1)–(3) implies that derivatives with respect to space (and time) are approximated in some way. The spatial and temporal urban sound field is a composition of waves, each with a different phase and amplitude. The discrete solution should resolve these waves, and the smallest wavelength to be solved (i.e. corresponding to the highest frequency) imposes the most stringent condition on the spatial grid spacing. For low order numerical techniques, i.e. techniques where the spatial derivative is approximated by a linear function, a discretization of about 10 discrete points are needed to resolve the smallest wavelength (the ppλ number), while some papers have investigated whether 6 points per wavelength are enough [124]. For a smaller ppλ number, the solutions suffer from dissipation or dispersion errors that are different per numerical solution technique.[2] For accurate predictions, these errors should be small. However, there is a trade-off regarding number of spatial points per wavelength and magnitude of the error.

To reduce the storage capacity of the computational method, including a priori knowledge of the exact solution reduces the amount of the total number of discrete points in a solution method. The boundary discretization methods (BEM, ESM) make use of this principle, as they utilise analytical point-to-point solutions in free space (BEM) or in cuboid geometries (ESM). Pseudospectral methods as PSTD also make use wave information; in PSTD the solution is decomposed onto a set of plane wave functions. As a result, only (part) of the boundary needs to be discretized in BEM

[2] Note that techniques may have additional subtleties regarding accuracy which are out of scope in this paper, as irregular eigenfrequencies in BEM and ESM.

and ESM, and PSTD only needs two spatial points per wavelength for high accurate results. Besides these methods, higher-order and compact schemes to solve derivatives are used in FDTD, but these methods have not been used to solve urban acoustics problems at microscale [29,125]. Table 2 gives an overview of the typical number of discrete points per smallest wavelength for the various numerical techniques of Sect. 2.6, as well as the number of discrete points needed in a 3D street with dimensions 20 m × 20 m × 300 m and an urban vertical section of 100 m × 2000 m (for studying propagation over roof height). The ppλ numbers are based on reported values in the cited work on urban acoustics, and should be interpreted as an indication rather than an identical comparison between the methods. If the boundaries need a finer mesh due to geometrical details, the ppλ criterion alone will not determine the total number of points as the average discretization will then be finer than from that criterion.

An important note is that the ppλ criterion determines the storage capacity, whereas computation time is not only dependent on the ppλ number, it is different per solution method and dependent on the way the method is implemented and parallelized.

2.9. Question 9: Have computational methods fully been developed?

Answer Due to both the improvement of computer power and access to parallel GPU and CPU programming in recent years, computational methods have been further developed but are not final yet.

The various computational methods that have been developed for urban acoustics have been cited in Sect. 2.6 and 2.8. For the application of the methods for the purposes as outlined in Sect. 1.3, there are still some developments to overcome. These development relate to:

- Further developments of methods: From the methods in Table 1, no method is fully appropriate for all aspects (i.e. a + mark). Further developments are ongoing to push the methods towards full appropriateness. For example, the low storage PSTD method still has drawbacks regarding the material representation as only frequency independent boundaries can be implemented. PSTD is currently further developed to overcome this issue, as well as to resolve its problem with not staircase type boundaries [126–128]. Also, BEM has been developed to include extended reacting boundary conditions [129], and a curvilinear approach is applied to FDTD to account for curved boundary shapes [130]. Besides, an approach to hybridise computational urban acoustics methods with engineering methods is ongoing [131].
- Acceleration of methods: Parallel implementation of codes on multithreaded CPUs or GPUs is getting more and more mature, see Table 1 and references in Ref. [117]. These developments have not reached their final stage and have not been optimised for all methods yet.
- Real-life applications: The purpose of the computational methods is to apply them to real-life scenarios. Besides simplifications that have to be made in the modelling approach due to limitations as reported in Table 1, implementations are often written in the form of in-house codes at academic institutes, making application of real-life cases sometimes cumbersome and also not accessible by others. In recent years, more real-life applications have appeared [107] and open source code initiatives have appeared [118]. These development have definitely not finalised yet. Finally, applying methods to real-life applications requires knowledge of geometries and material properties that are often not known completely. Getting the right input data is a big challenge and ways to retrieve them in a smart way, e.g. through inverse modelling techniques, should be explored.
- New methods: The applied mathematics community keeps studying methodologies that solve the wave equation at a lower computational cost. Such developments, as in Refs. [132,133] could finally reach the computational urban acoustics community and make real-life applications more feasible.

Table 2
Requirement of number of points per wavelength ppλ for accurate results in urban acoustics (as reported by cited work) and number of discrete points in a 20 m × 20 m × 300 m street, and 2D cross section of sound propagation over an urban area 100 m × 2000 m, up to the 1.6 kHz third octave band. A sound speed of c = 340 m/s has been used.

Method	Volume (V) or Boundary (B) discretization method	ppλ (−)	Number of points	
			3D street	2D urban section
			$\times 10^9$	$\times 10^6$
PSTD [31,32]	V	2	0.14	22.32
FDTD [27] [a]	V	10	17.68	558.03
TLM [33]	V	10	17.68	558.03
BEM [28]	B	6–10	0.02–0.05	0.13–0.21[b]
FM BEM [29]	B	6–10	0.02–0.05	0.13–0.21[b]
ESM [25,26]	B	10	0.05	0.21[b]
PE	V	10	17.68 [35]	558.03[b] [34]
Modal/FEM	B[c]	10	0.03[d]	-[e]

[a] A lower ppλ number is feasible, but has not been presented in urban acoustics applications.
[b] A discretization length of 4000 m is assumed.
[c] 2D intersections are discretized in the 3D model.
[d] 2D intersections every 10 m are assumed.
[e] Model is applied in 3D only.

2.10. Question 10: How will computational methods be used in 20 years from now?

Answer In twenty years from now, computational methods will according to the author be used for auralization as part of a real-time multi-sensory virtual reality (VR) system for urban areas, and will be utilized in smart urban sensor applications.

For research purposes at one hand and design of urban areas at the other hand, multi-sensory and dynamic VR systems are desirable. For research purposes, such a system can be used to investigate the role of sound and acoustics in a multi-sensory experience of an environment by the user of the system. For example, noise induced stress, annoyance and discomfort can be investigated under auralized situations. In the design of urban areas, the system will be a powerful tool to understand the consequence of e.g. proposed noise reduction measures, as it offers the possibility to listen to environments before and after an intervention. This is both useful for designers, acoustic consultants as well as in the communication to a wide audience, i.e. citizens that get informed about proposed changes in their neighbourhood. It allows designers to test ideas for urban areas for which they do not have a tool at the moment. VR systems that integrate visual and acoustic stimuli are currently under development [134], and more senses as touch, smell, air flow and (radiation) temperature are likely to be included [135]. Besides, coupling of real-time measurement data to predictions elsewhere in the city is also an ongoing topic [54], and this technique can make huge progress for generating real-time noise maps of cities, including distance propagation under actual meteorological conditions. The development of the methods as described in Sect. 2.9 should make this possible in the posed timeframe. It will enable the local city administration to carry out real-time noise monitoring and management, i.e. for supporting ad-hoc decisions as on turning down noise levels produced by loudspeakers in pubs or outdoor music events. Also, citizens can be informed on the predicted noise levels (i.e. due to highway traffic, air planes or a local outdoor concert) given the expected meteorological conditions. Finally, based on the data, cities can make strategic decisions as on placing noise control measures.

Finally, a shift in engineering methods can be established. Through the expected further developments of computational urban acoustics methods, they will be more attractive for prediction of realistic urban scenarios, and become available for consultants in the posed time frame. These methods will therefore replace current engineering methods in consultancy practice for scenarios where current engineering methods are less appropriate.

3. Summary

In this paper, methods for accurate prediction of sound propagation at the urban microscale are considered. Such methods have their role as reference model for engineering methods, for fundamental research in urban acoustics, for applied research in circumstances where engineering methods fail and likely for auralization purposes. The following has been discussed:

- Engineering methods give accurate predictions for a range of applications. Whereas computational urban acoustics method will not overtake the engineering methods for noise mapping purposes, they are needed for inner city environments, in particular when the line-of-sight between source and receiver is interrupted, and when meteorological effects influence sound propagation over rooftops;
- For good urban sound propagation predictions, physical input data is needed. As regards materials, the complex normalized surface impedances are need. For the geometry, the nature of the surface is important. Concerning meteorological conditions, the temperature and flow fields in the relevant computational domain should be known prior to starting an acoustic prediction. Finally, denser types of vegetation should be modelled because of their influence on sound propagation;
- A range of useful computational urban acoustics methods has been developed, but their practical use depends on further developments regarding computational efficiency, accuracy improvements and access to a wider audience.

The author foresees a role of computational acoustics methods in urban research, planning and design via a virtual reality system, which can also be useful for communication to a wide audience. Furthermore, the methods can play a role in real-time sound management in cities.

4. Expertise of the author

Dr. Hornikx is assistant professor in the chair Building Acoustics of Eindhoven University of Technology and holds a PhD in Applied Acoustics (2009) from Chalmers University of Technology. He is active for more than ten years in the field of urban acoustics. As a graduate student, he has worked with applying the Maxwell-Boltzmann collision equation for sound propagation on a macroscopic urban scale. Thereafter, he has further developed the parabolic equation (PE) method for 2D urban canyons and the equivalent sources methods (ESM) for 2.5D urban canyons. His major numerical accomplishment is the development of the pseudospectral time-domain (PSTD) method for generic 3D urban environments at microscale, including meteorological effects. Hornikx furthermore has gained expertise in the field by carrying out an extensive scale model study. PSTD calculations have been used to improve an engineering method for prediction of noise from road traffic. Also, radiation of noise from an automotive tailpipe noise, a major urban noise source, has been studied with PSTD. Furthermore, applied studies have been carried out to investigate the effect of potential urban noise mitigation measures as horizontal and vertical screens, vegetated façades, low parallel screens, vegetated roofs and trees. Hornikx has participated in five EC funded urban acoustics projects – Hosanna, Explica, Qside and currently openPSTD and SONORUS –, is currently leading a national project on urban physics, and supervises four PhD students on urban acoustics. Among current work is the development of the open source PSTD software. Hornikx has published about 20 peer reviewed journal papers on the subject and contributed to a book chapter.

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