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# The potential of building envelope greening to achieve quietness

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ABSTRACT

Reduction of noise is one of the multiple benefits of building envelope greening measures. The potential of wall vegetation systems, green roofs, vegetated low screens at roof edges, and also combinations of such treatments, have been studied by means of combining 2D and 3D full-wave numerical methodologies. This study is concerned with road traffic noise propagation towards the traffic-free sides of inner-city buildings (courtyards). Preserving quietness at such locations has been shown before to be beneficial for the health and well-being of citizens. The results in this study show that green roofs have the highest potential to enhance quietness in courtyards. Favourable combinations of roof shape and green roofs have been identified. Vegetated façades are most efficient when applied to narrow city canyons with otherwise acoustically hard façade materials. Greening of the upper storey's in the street and (full) façades in the courtyard itself is most efficient to achieve noise reduction. Low-height roof screens were shown to be effective when multiple screens are placed, but only on conditions that their faces are absorbing. The combination of different greening measures results in a lower combined effect than when the separate effects would have been linearly added. The combination of green roofs or wall vegetation with roof screens seems most interesting.



## 1. Introduction

The use of vegetation has become an essential aspect in urban planning nowadays. In densely built-up city centers, building envelope greening is often the only possibility to meet this demand. These measures have many ecological advantages too, ranging from increasing the thermal insulation of the building envelope and reduction of urban heat island effects [1–9], acting as a buffer for storm water [9–14], improving air quality and increased carbon dioxide uptake [15–17], increasing urban biodiversity [18–22], providing a visually pleasant environment [23], to even crop harvesting. In addition, also from an economical point of view, building greening seems interesting [24–27]. Recently, the noise reducing possibilities of such building envelope greening measures have been identified [28–32].

The presence of mainly acoustically rigid materials in cities (streets, bricks, concrete, glazings, etc.) leads to a strong amplification of the emitted sound from road traffic noise, and large sound pressure levels are observed in city canyons. The noise problem has indeed become one of the major environmental challenges in the urban environment. The WHO report "burden of disease by environmental noise" [33] quantified the many health-related effects by long-term exposure to environmental noise. The positive influence of quiet urban areas, as a possible mitigating measure, has been shown before [34–36] and has become part of European noise policy [37]. As a result, the sound environment in potentially quiet areas, like urban courtyards, has been studied in recent years [38–43]. Such courtyards are often shielded from direct exposure to road traffic noise, however, many of such places were found to exhibit noise levels that are too high to function as quiet areas, see e.g. references in [44]. Further reducing noise levels in urban courtyards is therefore needed such that citizens can fully benefit from access to quietness.

Applying building envelope greening and at the same time tackling noise issues can therefore be considered as a highly sustainable goal. A question of main concern is what type of building envelope measure is most efficient in achieving noise abatement. In this numerical study, 3 types of measures are considered namely green roofs, green walls and vegetated low-height noise barriers positioned near roof edges. Such green measures further help to increase the visual attractiveness of urban areas, which was shown to be important as well based on noise-related surveys [45].

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Low-height noise barriers were shown to be useful in road traffic noise applications at street level. This has been assessed by calculations with different numerical methods [46–50] and by scale modeling [46,48]. These devices can be placed close to the driving lanes, thereby yielding significant road traffic noise reduction. For sound propagating towards enclosed urban courtyards, edges of (flat) roofs are considered to be an important zone given that diffraction is the main sound path. All sound paths propagating towards the non-directly exposed side of a building have to interact with these edges. Placing barriers, even with a limited height, could therefore be quite efficient, although the relative increase in building height is very limited.

The noise reducing potential of green roofs has been identified before, by means of numerical simulations [28,29], by in-situ measurements [31] and laboratory measurements [32]. The substrate, which is a highly porous medium, is thought to exert the main effect. Sound diffracting over green roofs is especially attenuated since it propagates nearly parallel to the roof surface, increasing significantly the absorption coefficient as compared to other angles of incidence [51]. The vegetation present on the green roof will mainly have an effect at higher frequencies [31,32]. In case of canyon-to-canyon propagation, these high frequencies are in many cases sufficiently attenuated by the diffraction process itself, in contrast to low frequencies. As a result, the sound field in a shielded zone becomes typically low frequent [39]. Although there can be a complex interaction between vegetation and the substrate itself [52], this aspect is not considered here.

Roof geometry is an important aspect when dealing with the noise shielding of a building. It was shown in [53] that in case of an equal building volume, differences may amount up to 10 dBA, averaged over the courtyard façades in an urban setting. Building top height was considered to be a bad predictor for the noise shielding in an urban context. In Ref. [29] it was further indicated that roof shape and the presence of a green roof could interact. This aspect has been worked out in detail in this study.

In green wall systems, a growing substrate is placed in a confinement system at limited distance in front of the building façade. To resist gravity and to relax constructional demands, green wall systems usually consist of highly porous and low-weight materials, making them interesting sound absorbers. In urban streets, there are typically many reflections in between opposite façades. Upon each interaction with the green wall, part of the acoustical energy is absorbed. The strong amplification of noise by façade reflections in urban streets could be significantly reduced by the presence of green wall systems. This amplification effect is most pronounced in case of small street widths [54, 55]. Calculations in Refs. [38] and [42] showed that applying façade absorption in the source canyon is especially interesting to achieve noise abatement in an adjacent canyon. In the street itself, there is still an important contribution of direct sound reaching a receiver, making in-street applications of green walls usually less effective.

The focus in this study is on road traffic noise, which is the most important and widespread environmental noise source in the urban environment. The noise reducing potential of green roofs, green walls, and low-height vegetated roof screens is numerically assessed for receivers at the shielded side of a building. This study looks at what type of building envelope greening measure is most efficient, and which combinations of such measures are useful.

## 2. Computational approaches

Sound propagation between urban canyons is a complex problem, involving multiple reflections in between the façades of both the source canyon (e.g. street) and receiving canyon (e.g. a courtyard), involving diffraction over (complexly shaped) buildings, and the development of diffuse sound fields. For accurate predictions, full-wave numerical methods are therefore needed. Current engineering models are not capable of sufficiently capturing geometrical details like façade irregularities or to assess the importance of roof shape on diffracting sound waves.

In this paper, two full-wave methods have been applied, namely the finite-difference time-domain (FDTD) method, and the pseudo-spectral time-domain (PSTD) method. The combination of these two methods is beneficial, and allows increasing the reality value of the numerical simulations presented here. Both methods solve the same physical sound propagation equations (in a homogeneous, non-moving atmosphere) [40,56–58]. The main difference lies in the numerical discretisation. The FDTD implementation used here (see Ref. [56]) applies a lowest-order limited stencil approach, demanding a strong spatial and temporal discretisation. For accurate calculations, about 10 computational cells per wavelength are needed. PSTD solves spatial derivatives in a more efficient manner, leading to a spatial discretisation demand which is 5 times as low as in FDTD. As a result, PSTD allows full 3D calculations [57], while with common computing power, FDTD is usually limited to 2D applications.

FDTD, on the other hand, allows a more advanced treatment of material boundaries. In the current study, the interaction with porous substrates is essential. Such materials show frequency-dependent absorption characteristics. The Zwikker and Kosten model [59] can be elegantly introduced in the FDTD method, without further increasing computational cost. A discussion on the use of this model to represent growing substrates can be found in Ref. [28]. In addition, the use of a limited stencil scheme does not pose problems with multiple materials appearing very close to each other like e.g. at the air–bricks–substrate interface near building edges. In PSTD, modelling the interaction between sound waves and frequency-dependent boundary conditions is more limited. In the latter, it can be approached by introducing a second sound propagating medium with another density [63], however, not capturing the frequency-dependent behavior. As a result, additional calculations are needed when evaluating different frequencies. In FDTD, a single simulation provides information over a wide range of sound frequencies when applying appropriate post-processing.

This paper does not aim at developing or improving numerical models. The methods applied here have been validated before, by comparison with analytical solutions, by cross-validation with other numerical techniques for complex sound propagation problems, scale model measurements and full scale measurements [58,60–63]. In Appendix A, a cross-validation check between 2D-FDTD and 2D-PSTD is shown for the specific geometry under study. Very good agreement is observed between these two models in this complex sound propagation problem of two coupled city canyons.

## 3. Case study

### 3.1. Reference geometry

As a case study (see Fig. 1), two adjacent canyons with dimensions 19.2 m × 19.2 m (width × height) are considered, corresponding to six-storey buildings. The 3D configurations (Fig. 1c) include cross-streets and fully enclosed roadside courtyards. The cross-street dimensions are 9.6 m × 19.2 m, while the courtyard dimensions are 19.2 m × 19.2 m × 19.2 m (width × depth × height). The computational cost is reduced by treating this case as being periodic in the y-direction, which creates a long street aligned with building blocks as shown in Fig. 1c. To increase realism, depressions by windows (equal to 0.16 m) are explicitly modelled (Fig. 1a). The latter is responsible of building up a diffuse sound field in the

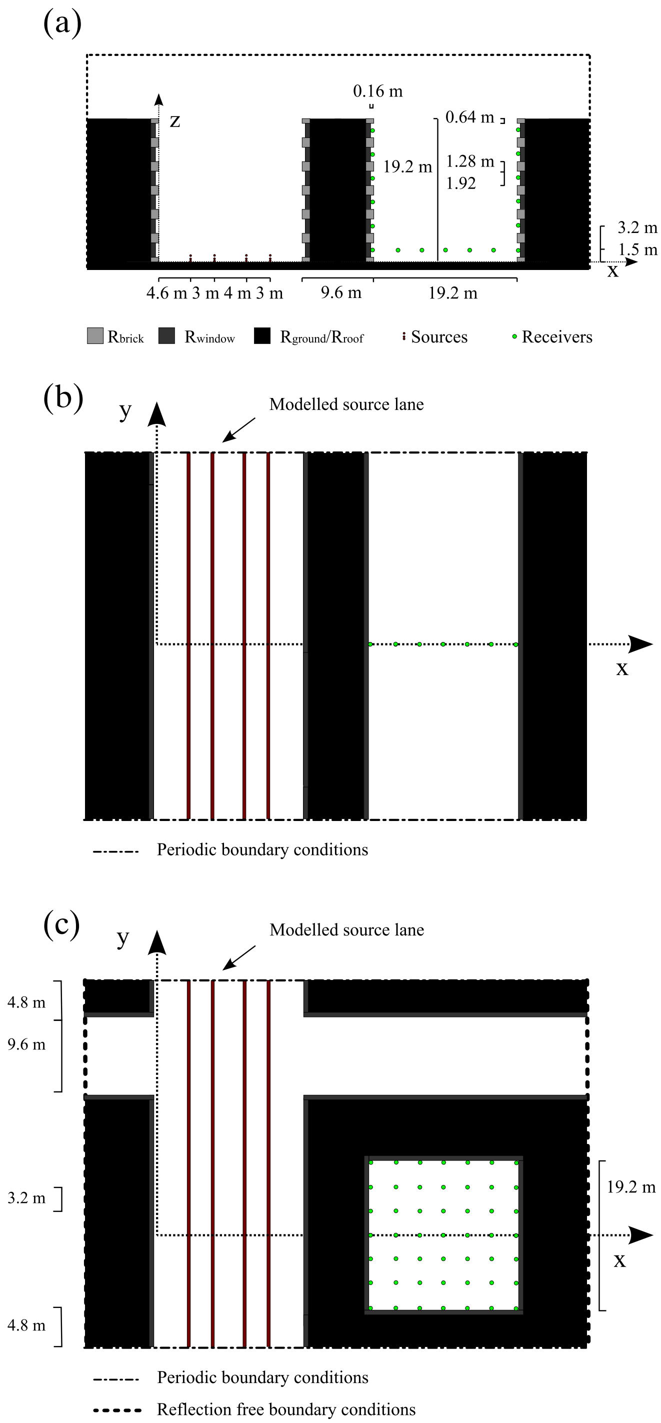


**Fig. 1.** Overview of the 2D geometry in cross-section (a) and plan view (b), and the 3D geometry in plan view (c).

canyons, which could influence the effectiveness of treatments [38,42]. All buildings have similar façades.

With FDTD, all treatments considered have been calculated in a 2D approach. Note that the 2D case actually implies that the courtyard is infinitely long, as illustrated in Fig. 1b. In 3D, a closed courtyard is formed (see Fig. 1c). With PSTD, for each type of treatment, 2D and 3D calculations have been performed to come up with a correction factor for this dimension reduction, as shown in Appendix B. In addition, an incoherent line source is modelled (which is more closer to traffic streams) and cross-streets are present. Note that 3D-PSTD calculations only are not sufficient, as 3D results are computed up to a sound frequency of 500 Hz. The correction for higher frequencies for each type of treatment has therefore been estimated based on PSTD results for the lower frequencies, and on the frequency-dependent effect of the treatment.

### 3.2. Building envelope greening measures

In total, 21 building envelope greening measures have been considered. An overview of the exact placement of these measures is given in Fig. 2. A categorization can be made in roof screens (cases A–C), green roofs (cases D–L), façade vegetation (cases M–Q), and combinations of treatments (cases R–U). In case of 3D calculations (confined courtyards), the roof edge screens and green roofs are applied to the full roof surface, as illustrated in Fig. 3. Wall vegetation is applied at the 4 courtyard facades for measures M and N, and along all other façades for measures O and P.

### 3.3. Receivers

Receivers are placed directly beside all windows along the façades in the courtyard. In addition, receivers are located along a line at pedestrian level (1.5 m). In the 3D cases, receivers are positioned along the 4 façades, and in a plane parallel to the courtyard floor. The spatial discretisation of the receiver lines equals 2 cm.

### 3.4. Road traffic noise source

Three uncorrelated source heights have been considered for a single traffic lane according to the Harmonoise/Imagine road traffic source power model, i.e. at $z = 0.01$ m, $z = 0.30$ m and $z = 0.75$ m [64]. This means that sound propagation from these three source points have to be calculated explicitly. Road traffic is assumed to have vehicle speeds varying uniformly between $v = 30$ km/h to $v = 70$ km/h, and to be composed of 95% light vehicles and 5% heavy vehicles. These parameters are of interest since these will change the frequency content of the sound emitted in the street. Traffic intensity is of no interest in the current study, since it only affects absolute levels, while the interest here is related to traffic noise insertion loss values. The latter is defined as the sound pressure level in the courtyard in absence of green measures, minus the ones in presence of green measures.

Whereas road traffic in urban areas consists of 2, 4 or even more traffic lanes, a single lane of road traffic is used in the current computations from an efficiency consideration. The validity of considering a single off-centre lane as a representation of the insertion loss of multi-lane traffic has been assessed in Appendix C. It is assumed that the cross-streets do not contribute to the noise levels in the courtyard.

Road traffic noise levels in courtyards are dominated by the lower frequency part of the road traffic spectrum, as shielding of traffic noise from the street canyon by diffraction increases with frequency. Noise levels at frequencies higher than the 1.6 kHz-1/3-octave band will be of limited significance in the courtyard, and would moreover strongly increase the computational cost in full-wave techniques. When looking at total A-weighted road traffic noise levels, calculations in [53] show some evidence for limiting to this frequency-band in a similar canyon-to-canyon sound propagation problem.

### 3.5. Material parameters

#### 3.5.1. Reference case

The brickwork at the façades is modelled with a frequency-independent reflection coefficient of either 0.82 [65] or 0.95 [66] (for normal incident sound waves). Clearly, the reference situation

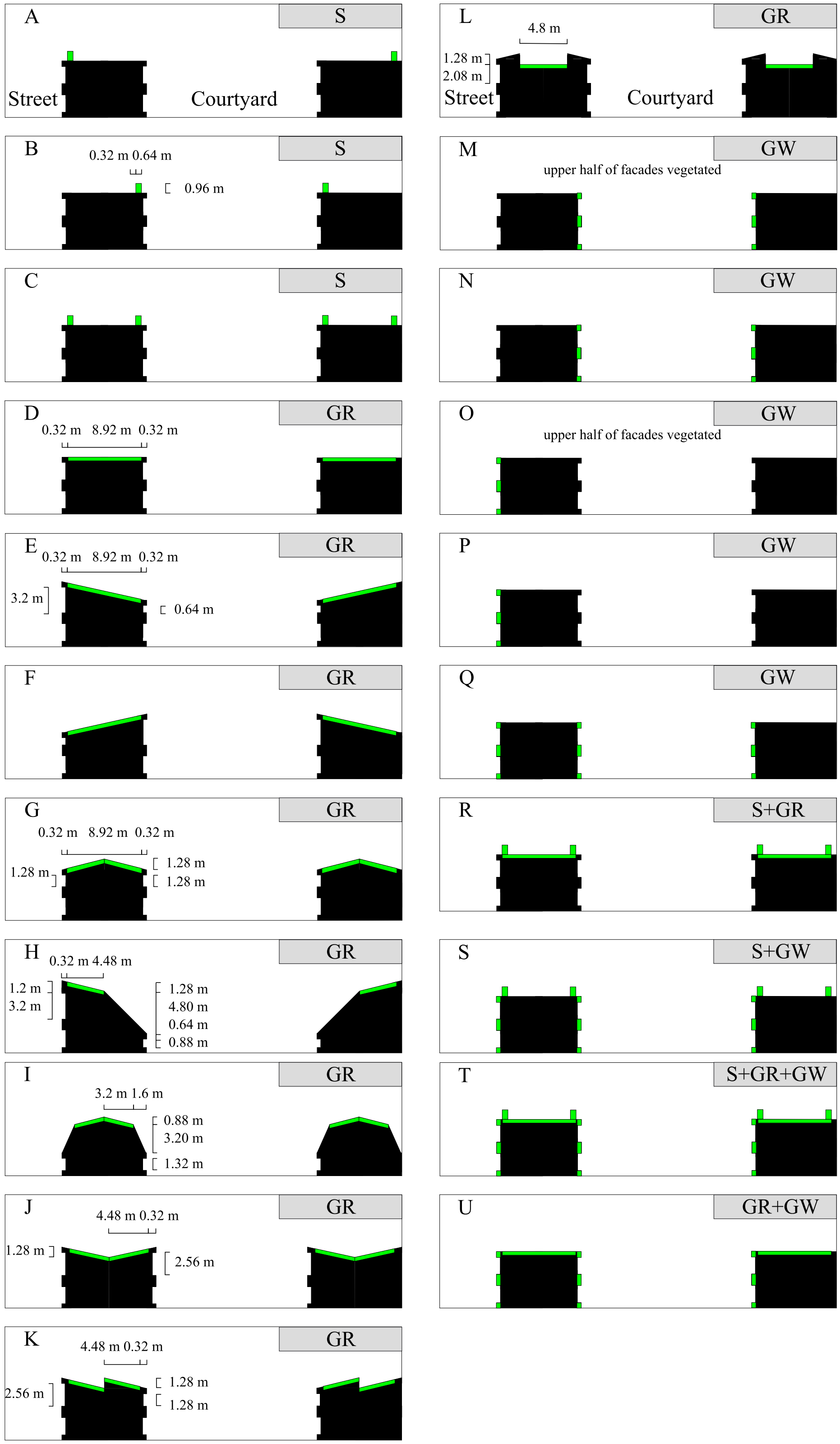


**Fig. 2.** Building envelope greening measures considered in this study, with dimensions and geometrical details. The zones where green measures have been applied are indicated.

for bricks in the canyons could be important when assessing abatement efficiency. In a conservative approach, the lowest reflection coefficient for bricks (which also include losses due to scattering) is used in order not to overpredict the effectiveness of a measure.

The street surface and roofs (non-greened parts) are modelled as rigid in the frequency range of interest. Glazings are modelled with a reflection coefficient equal to 0.975 for all sound frequencies considered.

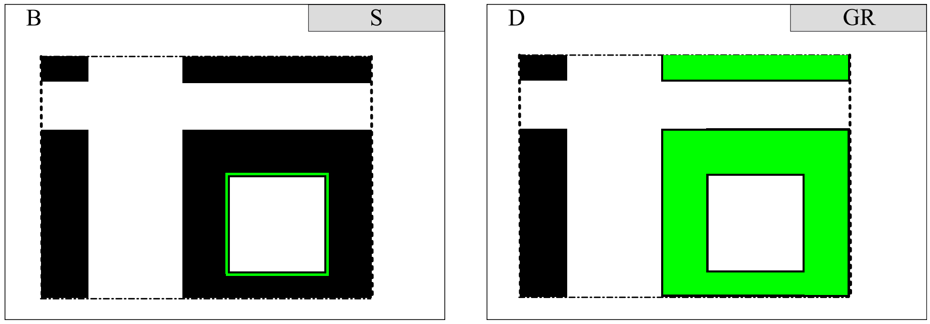


**Fig. 3.** Plan view indicating the location of roof screens (case B) and green roofs (case D) for confined courtyards.

*3.5.2. Green measures*

Measured frequency-dependent absorption characteristics of two samples of building envelope greening substrates are used. The first one is a semi-extensive 10-cm thick limestone-based green roof substrate as described in Ref. [32]. The second one is a 20-cm commercially available green wall substrate developed by Canevaflor [68]. The green roof substrate consists of 60% limestone, 20% loam and 20% organic matter. It has a porosity near 37% and a density near 1400 kg/m$^3$. The wall substrate is a mixture of fibers, perlite and mineral elements. It has a porosity of 76% and a density of 250 kg/m$^3$. The measured absorption coefficient for normal incident sound is shown in Fig. 4.

In FDTD, the absorption curves could be reasonably well approached by the Zwikker and Kosten rigid frame porous medium model. The best fit for both substrates is shown in Fig. 4. The green roof substrate is well approached by the FDTD model, and deviations in absorption coefficient stay below 2.5%. The green wall substrate shows a more complex behavior, with high absorption values already at lower frequencies. The latter is approached by means of applying a two-layered Zwikker and Kosten model in FDTD. The variation in absorption coefficient at frequencies above 500 Hz is not well-captured by the model. Note however that the absorption values are already high there. Given the nature of the decibel scale, it is mainly the relative errors in absorption coefficient that are of importance when assessing sound pressure levels. For deriving the 2D-to-3D correction factors, octave band absorption values derived from the fitted curves by FDTD are used in PSTD.

The measurements underlying the presented results were performed for substrates under dry conditions: this represents a well-defined and reproducible case when measuring, and allows assessing the maximum possible effect of the measures under study. The presence of water inside the substrate could strongly affect its absorption properties. In the extreme case when the porous medium is fully water-saturated, similar effects as for the (rigid) reference material could be expected.

The green wall substrate is used to cover the roof screens. An example of application of a green wall substrate to a low-height noise barrier at street level is described in Ref. [67].

Note that in the very low frequency range, the vegetated wall gives a more limited absorption coefficient than the modelled brickwork following ISO 9613-2 [65].

## 3.6. Results

*3.6.1. Averaging procedure*

In order to present general conclusions, a single number insertion loss value for the full courtyard has been defined by averaging over all receiver positions and over a range of realistic vehicle speeds in the street canyon. The averaged insertion losses are expressed as follows:

$$\overline{\mathrm{IL}}_{3D} = \frac{1}{VJ}\sum_{v=1}^{V}\sum_{j=1}^{J} 10\log_{10}\left[\frac{\sum_{k} L^{\mathrm{ref}}_{2D,A,v,j,k}}{\sum_{k} L_{2D,A,v,j,k}C_{2D-3D,k}}\right]$$

$$L^{\mathrm{ref}}_{2D,A,v,j,k} = 10^{\frac{L^{\mathrm{ref}}_{2D,v,j,k}-A_{w,k}}{10}}, \qquad (1)$$

$$L_{2D,A,v,j,k} = 10^{\frac{L_{2D,v,j,k}-A_{w,k}}{10}},$$

$$C_{2D-3D,k} = 10^{\frac{\overline{\mathrm{IL}}'_{2D,k}-\overline{\mathrm{IL}}'_{3D,k}}{10}},$$

with $\overline{\mathrm{IL}}'_{2D,k}$ and $\overline{\mathrm{IL}}'_{3D,k}$ the averaged insertion loss values from 2D- and 3D-PSTD calculations. The insertion loss is computed in dB(A) per receiver position $j$, and an arithmetic averaging is performed over all receiver positions and various traffic speeds $v$, ranging from 30 km/h to 70 km/h in steps of 10 km/h. $A_{\mathrm{w,k}}$ denotes the frequency-dependent value needed to calculate the A-weighting. All considered noise abatement schemes have been computed with 2D-FDTD. To extend the 2D-FDTD results to 3D insertion loss values $\mathrm{IL}_{3D}$, calculations with PSTD for various of the proposed noise mitigation schemes were carried out both in 2D and 3D, yielding frequency-dependent 2D-to-3D correction factors $C_{2D-3D,k}$. To limit the computational cost, this factor has been calculated for full octave bands, for frequencies up to 500 Hz, and for a few cases in each class of treatment (façade greening, green roof, roof screen). These computations are further used to make estimates for configurations that have not been computed by the 3D-PSTD method. While calculating standard deviations, the variation is $C_{2D-3D,k}$ has not been considered. The correction factors for the different cases are listed in Appendix B.

*3.6.2. Abatement efficiencies*

In Table 1, the single-value insertion losses are given for both the 2D cases, which can be considered as elongated courtyards, and 3D-cases representing confined courtyard as defined in Fig. 1. The reference situation has exactly the same geometry but in absence of green measures (ref a). For green measures applied to non-flat roofs, a flat rigid roof is taken as a reference as well (ref b). Also roof shape can be considered as an abatement strategy [53]. For all cases where green walls are involved, reference situations are considered with the two brickwork reflection coefficients of 0.82 and 0.95. In Fig. 5, the averaged insertion loss spectra are shown for all configurations considered.

*3.6.2.1. Roof screens.* The use of a single roof screen near the source canyon edges, or near the receiver canyon edges, only gives limited and very similar noise reduction. When placing two screens as in

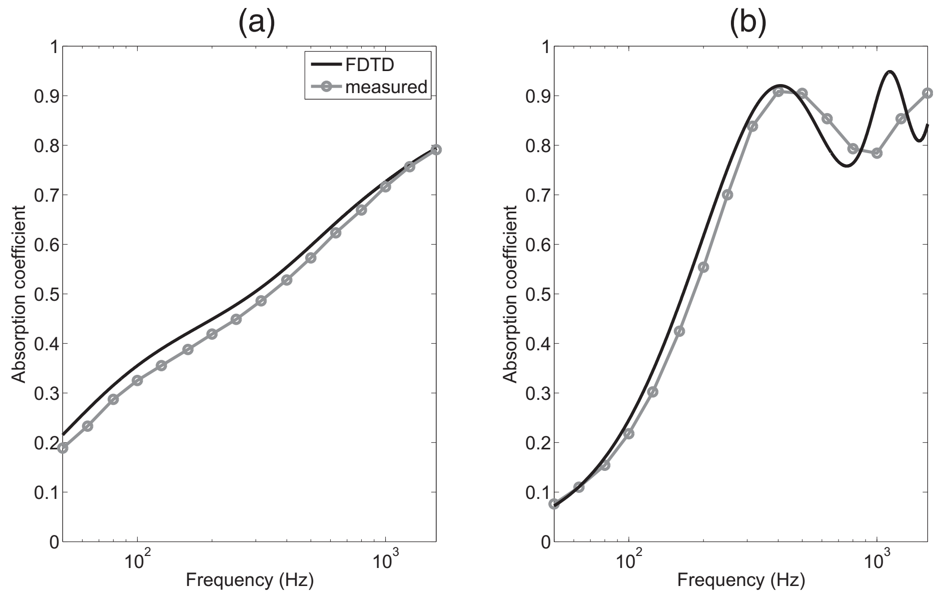


**Fig. 4.** Measured and simulated (FDTD) frequency-dependent absorption coefficient of a limestone based green roof substrate [32] (a) and the Canevaflor green wall substrate [68] (b).

cases A and B, it does not seem to be important whether to place them near the source canyon, or near the receiver canyon. However, placing the screen near the receiving canyon results in a much higher spatial variation of the noise reducing effect. When placing screens at both the source and receiver canyon edges, much larger effects were found. The (geometrical) combination of cases A and B results in case C, but shows a total effect which is higher than the simple addition of the separate effects. In case A and B, there is only a slight tendency for having larger effects with increasing frequency. In case C, the increase of the insertion loss with frequency is more pronounced, however, still limited compared to other measures. In an additional calculation, case C with rigid screens is evaluated. The 3D single-valued insertion loss equals −0.1 dBA, with a standard deviation of 0.7 dBA. This means that there is no net effect anymore, and the presence of rigid screens at the roof edges could even result in a slightly worse situation. In case of elongated courtyards, the effect of rigid screens can still be slightly positive (0.7 dBA). The presence of vegetation at the screen faces is thus essential.

*3.6.2.2. Green roofs.* The acoustical benefit of a green roof on a flat roof is predicted to be 2.4 dBA (3D). The efficiency of placing a green roof is strongly enhanced in case of tilted roofs E–I: single-valued insertion losses in the courtyard up to 7.5 dBA have been predicted. Compared to a green roof placed on a flat roof, the green roof area is larger, leading to a larger interaction zone between the porous medium and the diffracting sound waves over the roofs. In addition, the "soft" diffraction edge in the centre of the building in case I results in the maximum observed building envelope greening effect among the modeled ones.

Note, however, that in case of rigid non-flat roof, cases E–G result in a lower shielding compared to a rigid flat roof. The second reference case defined here (ref b) gives the insertion loss relative to a rigid flat roof. For cases E–G, a similar efficiency is then found as in case of a flat green roof (near 2.4 dBA). It can therefore be concluded that the non-optimal roof shape can be counteracted by the use of a green roof.

More complex roof shapes have been considered as well in this study. Case H, I and K show a somewhat lower insertion loss relative to a rigid roof of similar shape when compared to cases E–G. The green roof efficiency relative to a rigid flat roof is, however, higher. Especially the saw-tooth roof (case K) combination with a green roof seems interesting, and such types of roofs were already shown to be efficient only by their shape before [53]. Cases J and L, with a depressed part, show smaller green roof effects. Adding a green roof in case L hardly improves its shielding efficiency (ref a). The main effect is because of its shape (ref b). The reason for the smaller green roof effects for such depressed roof shapes is that sound is not forced to interact with the green roof: A straight line

**Table 1**
Overview of the different building envelope greening measures as described in Fig. 2. "S" means application of low screens at the roof edges, "GR" means application of green roofs and "GW" means application of green walls. Insertion losses (in dBA) are given in case of an elongated courtyard (2D) and in case of a confined courtyard (3D). The values are linear averages over all receiver positions inside the courtyard and over a range of vehicle speeds as described in Eq. (1). For the 2D case, the $C_{2D\text{-}3D}$ is set to zero. The values in between brackets are the standard deviations (in dBA). "ref a" is exactly the same geometry but in absence of green measures; absorption by bricks as in ISO9613-2 [65] has been applied. "ref b" assumes a rigid flat roof, and is added in case of non-flat roofs. "ref c" is used for all cases involving green walls, and assumes less absorbing bricks following Ref. [66].

| Case ID | Treatment type | IL2D (ref a) | IL3D (ref a) | IL3D (ref b) | IL3D (ref c) |
|---|---|---|---|---|---|
| A | S | 1.5 (0.2) | 0.7 | | |
| B | S | 1.6 (0.5) | 0.9 | | |
| C | S | 3.5 (0.8) | 2.7 | | |
| D | GR | 2.1 (1) | 2.4 | | |
| E | GR | 5.8 (1.8) | 6.8 | 2.6 | |
| F | GR | 5.5 (1.8) | 6.3 | 2.2 | |
| G | GR | 7.1 (2.3) | 7.5 | 2.3 | |
| H | GR | 4.6 (1.8) | 5.1 | 3.1 | |
| I | GR | 5.7 (2.2) | 5.9 | 3.8 | |
| J | GR | 2.1 (0.6) | 2.6 | 2.5 | |
| K | GR | 2.9 (1.1) | 3.5 | 4.2 | |
| L | GR | 0.5 (0.2) | 0.7 | 2.8 | |
| M | GW | 1 (0.6) | 1.2 | | 2.0 |
| N | GW | 1.5 (0.8) | 1.8 | | 3.2 |
| O | GW | 0.5 (0.3) | 0.4 | | 1.7 |
| P | GW | 0.9 (0.6) | 0.9 | | 3.4 |
| Q | GW | 0.9 (0.7) | 0.9 | | 4.4 |
| R | S + GR | 4.4 (0.9) | 4.3 | | |
| S | S + GW | 3.5 (1.5) | 2.8 | | 7.0 |
| T | S + GR + GW | 4.6 (1.6) | 4.0 | | 8.1 |
| U | GR + GW | 1.7 (1.6) | 1.7 | | 5.0 |

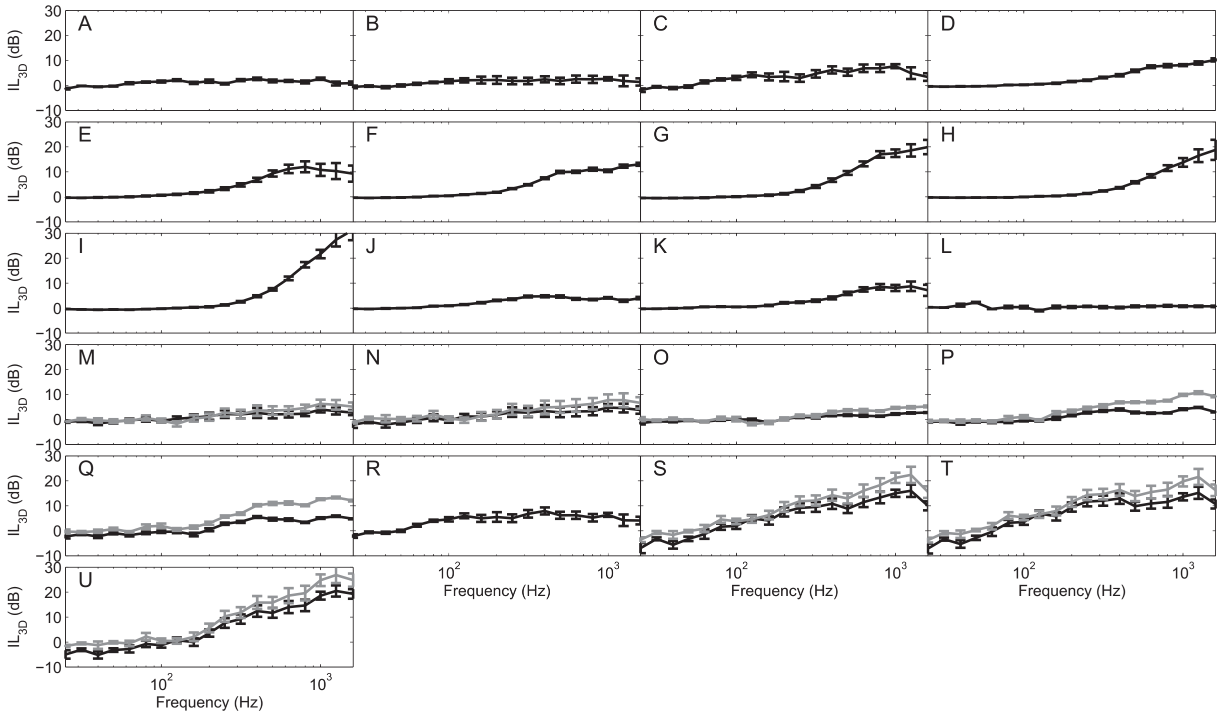


**Fig. 5.** 3D insertion loss spectra averaged over all receivers in the courtyard. The error bars have a total length of two times the standard deviations and were calculated for each 1/3-octave band separately. An overview of the abatement cases A–U is found in Fig. 2. The reference case is exactly the same geometry, in absence of green measures (ref a), for bricks with a reflection coefficient of 0.82. For cases M–Q and S–U, the spectral insertion loss in case of bricks with a reflection coefficient of 0.95 is shown as well (ref c).

can be drawn between the roof edges. The fact that there is still a green roof efficiency of about 2.6 dBA in case J shows that diffraction problems are more complex than such simple geometric considerations, stressing the need for use of full-wave numerical sound propagation models.

The 3D model results in somewhat larger insertion losses compared to the 2D approach for green roofs. In case of flat roofs, the insertion loss of a green roof was shown to be linearly proportional to its area, and consequently, the amount of absorption [28]. In 2D it is assumed that sound propagates normal to the building length axis, with a minimum interaction length between sound waves and the green roof. In the 3D cases, sound waves also travel obliquely over the green roof, leading to longer interaction paths.

The spectral insertion loss figures shows no effect at very low frequencies, while at higher frequencies very high noise reductions could be obtained. The spatial variation in the green roof effect is very limited. Only at higher frequencies, some variation in insertion loss is observed.

*3.6.2.3. Green walls.* Green walls covering the lower or upper half of the façades of the source or receiver canyons, and covering the full façades of the source or receiver canyon, have been considered. The assumptions for the reference case, and more precisely the properties for the brickwork, are essential to estimate the insertion loss. While assuming acoustically softer bricks, i.e. the use of a reflection coefficient of 0.82 [65], the effectiveness of green walls become rather modest: the maximum effect stays below 2 dBA. Also, some inconsistencies at very low frequencies appear since the measured absorption coefficients of the wall vegetation could become smaller than those of bricks. Calculations using a reflection coefficient of 0.95 [66], on the other hand, could be considered as yielding the maximum possible effects: an insertion loss of 4.4 dBA in case of fully vegetated source canyon façades. The acoustical properties of the bricks mainly affect the efficiencies of wall vegetation applied to the source canyon.

Greening the source canyon shows to be less effective in case of the softer bricks, but could be highly effective in case of more rigid façade elements in the untreated situation. The main zone of concern regarding vegetated façades at the street side seems the upper half of the street. Fully vegetating the source canyon does not give additional benefits compared to only treating the upper half in case of soft bricks, while additionally 1 dBA can be gained in case of rigid bricks. The presence of wall vegetation in the lower part only results in a rather limited insertion loss. This can be explained by the fact that direct sound propagation from the source to the building roof edge is an important contribution to the sound pressure levels in the courtyard. Placing absorption near the diffraction edges was shown to be essential to achieve noise reduction before [42].

Courtyard greening shows to be more efficient than street canyon greening when assuming acoustically softer bricks. Fully greening the courtyard façades is beneficial compared to only putting a green wall in the upper half, showing the importance of keeping reverberation low in the receiving canyon as well.

Courtyard greening results in much larger spatial variation of the noise reducing effect than street canyon greening. The insertion loss spectra show an increase of noise reduction with frequency, which can be attributed to the increase in absorption with frequency. Street canyon greening results in a less consistent behaviour in function of sound frequency.

*3.6.2.4. Combinations of treatments.* The combined effect of building envelope greening measures cannot be simply predicted as the sum of the individual insertion loss values. Similar findings have been reported with relation to urban acoustics before [38,42,46]. In all cases defined here, a lower combined effect is obtained.

The combination of green walls and green roofs (cases T and U) suffers from loss of individual efficiency. This is caused by the fact that both treatments are in essence based on absorption by porous media, which is governed by the same physical processes and which is most efficient in the high frequency range. By further reducing the high frequency content (by adding more substrates), other frequency components become dominant. Due to the logarithmic nature of the decibel scale (and human hearing), no additional benefits are then obtained when looking at total levels. This is even enhanced since these high frequencies already become less intense after diffraction over buildings.

The presence of roof screens and green roofs (case R) is closest-to-being-additive among the combinations considered. Less than 1 dBA is lost by combining these measures. For the cases involving green walls, this loss of efficiency by combining ranges from 2.6 to 5.1 dBA. In case of assuming more rigid bricks, these loss factors are largest. Combining green walls and roof screens (case S) seems interesting, and leads to a combined efficiency of 7.0 dBA under the rigid-brick assumption.

Combining wall vegetation along each façade in both source and receiver canyon, a green roof, and roof edge screens leads to a combined reduction of 4 dBA (soft-brick case) and 8.1 dBA (rigid-brick case).

As a conclusion, combining several building envelope greening measures could be used to further enhance acoustic shielding, although this cannot be considered as (cost-)efficient measures. Especially combinations between green walls or green roofs and roof screens seems beneficial, since other physical noise reducing processes are involved. Green walls and green roofs are less interesting to combine.

## 4. Conclusions

The potential of building envelope greening measures at residential urban areas is numerically studied. Focus is on road traffic noise propagation from a street to a nearby courtyard. The benefits of two full-wave numerical techniques, namely FDTD and PSTD, have been combined. The former has been used to study the proposed noise reduction measures in 2D (which is equivalent to elongated courtyards) and the latter has been used for extending the 2D results to the 3D configuration (confined courtyards). Although the realism of the calculations has been increased by applying such correction factors, the influence on the averaged road traffic noise insertion loss over the courtyard stays within 1 dBA. This correction was shown to be related to a specific measure, but there is no general positive or negative trend.

Green roofs have the highest potential to enhance quietness at non-directly exposed façades and in courtyards. Favorable combinations of roof shape and green roofs have been identified, leading to reductions up to 7.5 dBA in confined courtyards. Low screens at roof edges were shown to be effective, but only when they consist of absorbing faces. The effect of wall vegetation strongly depends on the assumptions on the material parameters in the reference case. Street façade vegetation leads to most road traffic noise reduction when the materials in the untreated source canyon are close to being rigid. Treating the upper storey's in the street is most efficient. In case the material properties in the untreated street are acoustically softer, wall vegetation in the courtyard is more efficient. Fully vegetating the receiving canyon has an additional advantage compared to only treating the upper half.

The combination of building envelope greening measures results in a lower combined effect than what a simple addition of the separate effects would give. The combination of green roofs or wall vegetation with roof edge screens seems most efficient. The combination of green roofs and green walls does not show to be efficient in road traffic noise applications.

Green roofs, and wall vegetation in the street canyon were found to reduce noise rather independent of the position of the receiver in the courtyard. Roof screens and wall vegetation in the courtyard result in much higher spatial variation in acoustical efficiency.

## 5. Discussion

The cases defined in Fig. 2 assume that the dominant sound paths are those diffracting over the roof. However, in case of openings connecting the street and courtyard, such openings can become the main sound paths. As a result, the measures studied here would be much less effective. Applying absorption at courtyard openings was shown to be an effective measure [69].

Distant traffic has not been considered in this study. The only contributions come from the adjacent street canyon. Typically, long-distance contributions become low frequent, and could be of importance under downwind conditions. Clearly, façade treatments in the adjacent street canyon will not have any effect in the courtyard when distant traffic is dominant. Roof treatments or façade greening in the courtyard itself could still be of interest in such a case. The urban morphology near the courtyard under study will also have an influence. Green roofs and façade treatments will behave differently when the building over which sound diffracts is higher or lower than the surrounding buildings.

The environmental noise source studied here is road traffic. Although green roofs could potentially be useful to limit other noise sources like, e.g. fan noise from air conditioning units positioned on roofs, the insertion loss values presented in this study cannot be simply applied to such cases.

As indicated before, the calculations presented here serve as examples of the maximum noise reduction that could be obtained when using building envelope measures. The water content of the substrates could have an important influence on the acoustic absorption [70]. Clearly, a minimum water content is needed to grow vegetation. To predict the acoustic absorption, the exact distribution of the water inside a porous material could be of concern [71,72]. The dynamics of water transport inside the growing substrate and runoff characteristics after rainfall events need further study to assess the long-term noise reducing effect. Given the measurements reported in Ref. [68], it is expected that in case of green walls the reduction in absorption by increasing the moisture content in green wall substrates could be rather limited.

The calculations have been performed for a canyon with width-to-height ratio of 1. For narrow canyons, the insertion loss of the building greening measures was shown to be slightly enhanced as illustrated by two examples presented in Appendix D.

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## Appendix A

A detailed cross-validation between FDTD and PSTD for the reference case (2D) has been performed. A single source position at $(x,z)=(6.01,0.01)$ is considered (see Fig. 1(a)). Results are shown along the left ($x = 28.64$ m) and right façade ($x = 48.16$ m) in the non-directly exposed canyon, and along a horizontal line at $z = 1.5$ m parallel to the courtyard floor. Results are expressed relative to free field sound propagation. This means that the same source–receiver locations are used in the reference case, but now in the absence of any boundaries (so only geometrical spreading is included). The positive values show that in case of very low frequencies, sound is clearly amplified. At higher 1/3-octave bands, diffraction by the tall buildings strongly decreases sound pressure levels in the shielded canyon and negative values are obtained. The comparison shows very good agreement between both models. Along the right façade ($x = 48.16$ m), more oscillations are predicted with PSTD at the 250-Hz band, which are not predicted by FDTD. The oscillations could be understood as a standing wave in the window depressions. The standing wave propagates parallel to the window surface, which is the angle of incidence to the boundary where PSTD and FDTD are known to deviate most. At 1 kHz, the agreement is perfect. The good agreement in the basic reference setup allows using correction factors in between the different numerical models.

**Table B.1**
Correction factors $C_{3D-2D}$ (in dB) to calculate the 3D insertion loss based on 2D insertion loss simulations.

| Case ID | 31.5 Hz | 63 Hz | 125 Hz | 250 Hz | 500 Hz | 1000 Hz | 2000 Hz |
|---|---|---|---|---|---|---|---|
| A | 0 | −0.7 | −2.1 | −0.4 | −0.3 | −0.3 | −0.3 |
| B | 0 | −0.7 | −2.1 | −0.4 | −0.3 | −0.3 | −0.3 |
| C | 0 | −0.7 | −2.1 | −0.4 | −0.3 | −0.3 | −0.3 |
| D | −0.2 | −0.1 | 0.2 | 0.7 | 2 | 2.8 | 3.5 |
| E | −0.1 | 0 | 0.3 | 1.1 | 3.2 | 3.8 | 3.5 |
| F | −0.2 | −0.1 | 0.3 | 1.1 | 3.5 | 3.6 | 4.6 |
| G | −0.2 | 0.1 | 0.1 | 0.8 | 1 | 3.4 | 2.5 |
| H | −0.1 | −0.1 | 0.1 | 0.4 | 2 | 4.9 | 6.9 |
| I | −0.2 | −0.2 | 0 | 0.5 | 2.7 | 7.7 | 11.3 |
| J | −0.1 | 0 | 0.5 | 1.2 | 1.6 | 1.4 | 1.4 |
| K | −0.1 | 0.2 | 0.2 | 0.8 | 2 | 2.8 | 2.4 |
| L | 0.1 | −0.1 | −0.3 | 0.3 | 0.2 | 0.3 | 0.3 |
| M | −0.2 | −0.1 | 0 | 0.1 | 0.7 | 0.7 | 0.7 |
| N | −0.4 | −0.2 | 0 | 0.2 | 1.5 | 1.5 | 1.5 |
| O | 0.2 | 0.2 | 0 | −0.3 | −0.4 | −0.4 | −0.4 |
| P | 0.2 | 0.2 | 0 | −0.3 | −0.4 | −0.4 | −0.4 |
| Q | 0.3 | 0.4 | 0 | −0.6 | −0.8 | −0.8 | −0.8 |
| R | −0.2 | −0.8 | −1.9 | 0.3 | 1.7 | 2.5 | 3.2 |
| S | −0.1 | −0.5 | −2.1 | −0.8 | 0.4 | 0.4 | 0.4 |
| T | −0.3 | −0.6 | −1.9 | −0.1 | 2.4 | 3.2 | 3.9 |
| U | −0.4 | −0.1 | 0.2 | 0.6 | 3.1 | 3.9 | 4.6 |

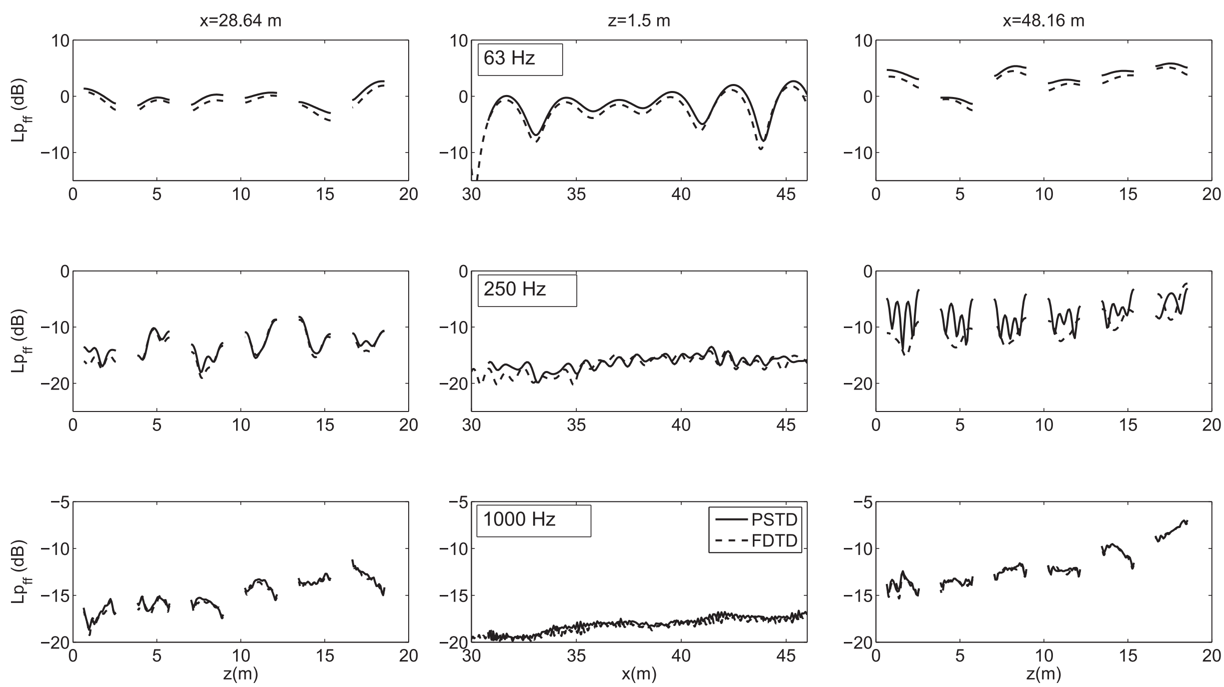


**Fig. A.1.** Sound pressure levels, relative to free field sound propagation, along the left façade in the courtyard ($x = 28.64$ m, left column), along the courtyard width ($z = 1.5$ m, middle column), and along the right façade in the courtyard ($x = 48.16$ m, right column). Three octave bands (63 Hz – first row, 250 Hz – second row, and 1000 Hz – last row) have been considered.

## Appendix B

In Table B.1, the correction factors to calculate the insertion loss of confined courtyards (3D-case), based on simulations for elongated courtyards (2D case), are presented. These factors have been calculated based on 2D-PSTD and 3D-PSTD calculations. These factors are shown for full octave bands; linear interpolation has been performed to get correction factors in 1/3-octave bands.

Analysis of the 2D-to-3D corrections reveals that the insertion loss in the idealized 2D configurations is close to the ones in the 3D configurations. Differences when applied to total A-weighted road traffic noise stay on average within 1 dBA. Depending on the type of measure, some trends can be observed. The 2D results leads to a small underprediction in case of green roofs, typically between 0.5 and 1 dBA. The effect of low barriers on the roof edges become slightly higher in 2D, but this difference is lower than 0.5 dBA. Courtyard façade greening gives a lower effect in 2D of about 0.5 dBA, while street façade greening effects are slightly overpredicted. Note, however, that in case of very elongated courtyards, the 2D calculations will be closer to reality than the 3D case presented here. This comparison shows that there is no consistent trend to over- or underpredict the single number insertion loss in the courtyard when using the simplified 2D configuration.

The dimensionality corrections for the combination of treatments are approached by linearly adding the corrections of the separate effects.

## Appendix C

Whereas road traffic in urban areas consists of 2, 4 or even more traffic lanes, a single lane of road traffic is used in the current computations to reduce the computational cost (with a factor of 4). To assess the validity of this approach, additional calculations (2D-FDTD, ref a) were carried out to compare the effect of green walls placed at all courtyard façades (case N). Three source heights have been considered in each lane in order to apply the Harmonoise/ Imagine road traffic source power model. The averaged noise insertion losses are 2.0 dBA (0.7), 1.5 dBA (0.7), 1.6 dBA (0.7) and 0.5 dBA (0.7), for the first, second, third and fourth (=closest one to the central building) traffic lane, respectively. The global insertion loss of the 4 lanes (assuming same speeds, equal traffic intensity and traffic composition in each lane) equals 1.4 dBA. Only considering the off-centre lane number 2 (1.5 dBA) is a good estimate of the multi-lane traffic insertion loss, and is used standard in all calculations in this study.

## Appendix D

Canyon-to-canyon sound propagation is influenced by their width-to-height ratios. Inside narrow streets, larger sound pressure levels are observed compared to levels in wider canyons due to the larger importance of street reverberation [54,55]. Shielding caused by narrow canyons, on the other hand, is somewhat larger [38]. Also the efficiency of noise reducing measures in adjacent canyons tends to be larger, as discussed in [42]. Similar effects are therefore expected for the green measures applied in this study.

The effect of two types of abatements namely C (roof screens) and N (façade vegetation along all façades in the courtyard) has been calculated for a narrow canyon (with a width of 9.6 m instead of 19.2 m). This means that the narrow canyons have a width-to-height ratio of 0.5, compared to 1 in the standard case used in this numerical study. The efficiency of both treatments is indeed somewhat enhanced in the narrow canyon. The insertion loss of the roof screens is about 0.6 dBA higher. For the wall vegetation, this difference is limited to 0.3 dBA. These rather small differences show that the insertion losses obtained in this study have a wider applicability. As also illustrated with this example, the influence of street and courtyard geometry will depend on the specific building envelope greening measure.

**Table D.1**
Single-value insertion losses (in dBA), as calculated with Eq. (1), for cases C and N, in case of city canyon width-to-height ratios of 1 (canyon width 19.2 m) and 0.5 (canyon width 9.6 m). Values are provided for elongated courtyards ("ref a" has been used).

| Case ID | Mean IL2D (canyon width = 19.2 m) | Mean IL2D (canyon width = 9.6 m) |
|---|---|---|
| C | 3.5 (0.7) | 4.1 (0.9) |
| N | 1.5 (0.7) | 1.8 (0.8) |

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