



# 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.

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## 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 Zwicker 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  $19.2\text{ m} \times 19.2\text{ m}$  (width  $\times$  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  $9.6\text{ m} \times 19.2\text{ m}$ , while the courtyard dimensions are  $19.2\text{ m} \times 19.2\text{ m} \times 19.2\text{ m}$  (width  $\times$  depth  $\times$  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  $0.16\text{ m}$ ) are explicitly modelled (Fig. 1a). The latter is responsible of building up a diffuse sound field in the

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