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Improving the noise reduction by green roofs due to solar panels and substrate shaping — Source link

Timothy Van Renterghem

Institutions: Ghent University

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TITLE

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AUTHOR

Timothy Van Renterghem

ABSTRACT

The urban fabric largely consists of acoustically rigid materials. This not only affects sound pressure levels in streets, but also how sound propagates towards the back side of a building or to connected urban canyons. A green roof is a practical solution to have roof absorption, mitigating diffracting sound waves. Flat green roofs were shown to provide roughly 3 dBA urban road traffic noise reduction relative to a common flat rigid roof. Although already relevant, it has been numerically studied in this work how the green roof insertion loss of flat roofs can be further increased. Solar panels on green roofs were found to significantly decrease sound pressure levels at the shielded building facade, up to 5 dBA on top of the insertion loss of granular substrates. Polyurethane foam slabs as green roof substrates provide relevant shielding when placed on a series of hollow trapezium-like cores of sufficient height.

KEYWORDS

Sound propagation, building skin, building envelope greening, green roofs, sustainable buildings, quiet side

1.INTRODUCTION

Street surfaces and building facades most often consist of acoustically rigid materials like glass, concrete, tiles, bricks, pavements, and so on. As a consequence, there is often a strong increase in sound pressure level due to the multiple reflections in between opposing building facades and on the street surface. Heutschi[1] proposed a simplified model for the so-called “building correction” for typical street geometries based on a ray-tracing numerical model. Parameters that were identified as relevant were the height of the facades, width of the street (canyon), the absorption coefficient of the facades, the degree of diffusion and source/receiver positioning. Thomas et al.[2] proposed the “reflection ratio”, an impulse response based indicator, which was measured in 99 real streets in a city centre. The main influencing parameters were street width, facade height and facade roughness. The large number of reflections inside the street clearly affect the sound intensity incident on the directly exposed facade of a building. Although increasing the acoustic insulation of a facade might be helpful to mitigate noise issues, window opening habits might strongly deteriorate the overall facade insulation and consequently increases the noise levels to which dwellers are exposed indoors[3,4]. Although one might opt for windows that cannot be opened or try to minimize their surfaces, such choices can conflict with preferences and a lower overall perceived comfort. There is a bulk of research[5-9] showing that there are various ways to reduce this street amplification. There are two major directions to follow namely increasing the diffusivity of the facades or increasing the absorption rate of the materials used (in a fixed geometry), similar to what is commonly done in room acoustic design.

Street and building (facade) geometry not only affect street acoustics and directly exposed facades, but also sound propagation towards the back side of a building or to a connected urban canyon[10-12]. Changing the properties of the street canyon can strongly change its radiation efficiency/directivity pattern. As a consequence, abatements taken at the loud side might also affect the shielded facade. This is especially important to achieve a quiet side.

The presence of a quiet façade was convincingly shown to be positive for the perception of environmental noise at home in many studies[13-17]. This measure could be potentially explained by providing dwellers a coping mechanism or some kind of compensation for their highly noise exposed building side. Residents could literately escape from excessive noise levels depending on their activities, or have the possibility to locate noise-sensitive rooms (like a study room or bedroom) at this non-directly exposed side.

During sound propagation to the back side of a building, roof shape and roof materials become relevant. Roof shape was shown to be able to drastically change the diffraction pattern towards its shadow zone in a dense urban setting[18]. The acoustical properties of the roof are important as well; in case of rigid roof reflections, pressure doubling (+ 6 dB) will occur during diffraction. Although a closed row of houses could be - in theory - a rather efficient noise barrier, the combination of a highly trafficked urban street (canyon), street reverberation and roofs acting as a perfect mirror can lead to exposure levels that are often much too high to benefit from the aforementioned quiet side effect[13].

Green roofs were found to have good absorbing properties, and are thus an interesting candidate to increase roof absorption. Clearly, the dominant sound path should then be the one diffracting over the roof (and, e.g., not along vertical edges as one would have in case of an isolated tall building). Indeed, diffraction theory stipulates that the absorption characteristics of the faces making the diffracting object have an important effect on the sound pressure levels in its shadow zone. Green roofs are especially interesting as they have been specifically designed to be placed outdoors during many years and with a limited amount of maintenance. In addition, there are many ecological and economical benefits[19]. Most common (porous) sound absorbing materials used indoors are not at all suited to be positioned along the outer building skin.

In this paper, green roof acoustics are first discussed from a more theoretical point of view. Next, literature was scanned for proofs of concept of the acoustic benefits one might get by green roofs. There is a focus on the sound absorption characteristics and the related sound pressure level reduction during diffraction over roofs. Both numerical work and real-life case studies will be considered. In a final section, it has been numerically studied how the sound shielding by a flat green roof can be further increased by considering solar panels and by shaping green roof material. Sound transmission reduction through the roof system, by the presence of a green roof, is another acoustical benefit[20,21] that will not be discussed in this work.

2.GREEN ROOF ACOUSTICS

2.1.Layered build-up and variety

Green roofs consist of a porous growing substrate, water storage fabrics, air voids and a plant layer. Together, they form a multi-layered system with a complex acoustic behavior. The growing substrates in extensive green roofs are mostly granular materials with open pores, which is an essential material property to allow sound penetration and interaction with the particles, leading to sound absorption. As with common porous materials, sound absorption generally increases with frequency and layer thickness. The absorption characteristics of the constituting parts of a growing substrate were separately measured in Ref. 22; sand was shown to have the lowest absorption coefficient in such mixtures, while organic matter could make substrates reasonably good sound absorbers[22]. Given the wide variety in layer built-up and thicknesses, absorption spectra can be quite diverse[19].

2.2. Shearing interactions

Interactions between sound waves and the green roof occur during diffraction, so at near-grazing incidence. Following ray-theory, this leads to cancelling of the waves shearing over the roof and those reflected from the substrate. In practice, this cancelling will be incomplete since sound waves do not propagate fully parallel with the green roof. In addition, there will be so-called ground waves that can be prominent at (very) low sound frequencies. This is similar to what is observed for a source positioned at zero height on natural grounds outdoors as discussed in detail in Ref. 23. As a result, there is hardly any improvement relative to sound propagation over a rigid ground/roof in the low frequency range, so limiting the overall effect.

2.3. Water

Adding water to any porous material deteriorates its absorbing properties. Various complex effects might appear like a reduction in the effective layer depth, substrate particles swelling, clogging of pores and exchange of water in between the different layers constituting the green roof system. When fully saturated, the substrate surface approaches a perfectly reflecting plane. Impedance tube measurements during (unforced) evaporation (indoors) of an initially fully saturated green roof substrate show the increase in absorption coefficient with decreasing soil moisture content[19]. Especially in the higher frequency range, a large variation, covering the full range between no absorption at all and full absorption, can be observed[19].

2.4. Vegetation layer

The influence of the plant layer on absorption is less obvious. Although it was shown that specific plants are able to absorb acoustic waves reasonably well[24], the acoustic system formed by plants on top of a porous material is more complex. Measurements at normal incidence show that in the low frequency range, there is a slight enhancement of the absorption of the plant-substrate system, while at higher frequencies plants lead to a decreased absorption relative to uncovered substrates[22,25-26]. A large pack of leaves on a porous substrate, however, was measured to increases the absorption coefficient at all sound frequencies[27].

The green roof acoustic properties might significantly change over time. Water dynamics, plant community development and compaction of substrates will largely contribute to this temporal variation.

3.PROOF OF CONCEPT

3.1.Numerical work

Full-wave numerical techniques, capturing the previously mentioned complex wave phenomena, are needed to study the parameters of concern with relation to the potential noise reduction obtained by a green roof. A comparison with common rigid roofs can then easily be made in (idealized) urban geometries.

Simulations with the finite-difference time-domain (FDTD) technique in Ref. 28 predict useful positive insertion losses (relative to a fully rigid roof) at frequencies above 250 Hz. A linear relation between sound level reduction and the fraction of the (flat) roof covered by the green roof was found[28]. In case of shallow substrates, the presence of an optimum substrate depth in function of sound frequency was revealed[28].

The diffraction over a building, the green roof absorption characteristics, a typical road traffic noise spectrum and also the A-weighting are all strongly frequency dependent. The overall noise reduction in dBA provided by a green roof in a road traffic noise case is therefore not easily estimated. Numerical analysis, focusing on road traffic noise mitigation, showed that with increasing vehicle speed the green roof insertion loss becomes larger given the shift to more high frequent source spectra[29]. Simulations[29,30] further showed that the positive effect of placing a green roof on a non-flat roof is more pronounced than on a flat roof. This can be explained by the additional interaction length between sound waves and the green roof in such cases.

Green roofs were found not only to help when sound propagates over a (complete) building, so involving multiple diffracting edges, but also in case of sound propagation over part of a building. Such a case occurs e.g. when a facade overlooks a green roof placed on a building extension and involves a single-edge diffraction[29]. The noise reduction will then depend on the position of the source, the height and width of the building extension and the specific location along a facade[29]. At lower and thus partly shielded parts of the facade, significant road traffic noise reduction is possible by the green roof (exceeding 5 dBA at 70 km/h[29]). Given the single edge diffraction only in such a case, higher frequencies are relatively more important, and these are reduced to a larger extent.

3.2.Measurements

A set of 5 in-situ measurements of sound propagating over flat, extensive green roofs (relatively dry state) is described in Ref. 31 and later on recalculated to total A-weighted road traffic noise insertion losses[19]. Since such measurements were performed just before and just after the placement of the green roof, with a controllable noise source and with an identical source-receiver configuration, a direct and accurate measurement of the insertion loss was possible. The single diffraction cases showed road traffic noise insertion losses between -2.4 and 5.5 dBA, while the double diffraction cases yielded 2.2 to 5.1 dBA. In the single diffraction cases, changes in interference pattern relative to non-vegetated rigid roof tops could lead to negative insertion losses at specific receiver zones. For the double diffraction cases (flat roofs), the green roof improvement showed to be less frequency-dependent and in all cases positive[31]. Another flat green-roof in-situ measurement[32] and a street canyon scale model at scale one tenth[33] confirmed the noise reduction of 2 to 4 dBA in enclosed courtyards.

A long-term in-situ diffraction experiment[34] near the edge of a building equipped with an extensive green roof, subject to natural precipitation, showed that sound propagation was mainly sensitive to the volumetric water content (VWC) of the substrate in a particular frequency range, namely between 250 Hz and 1250 Hz[34]. The difference in the noise attenuation between 10 % VWC (relatively dry state) and a fully saturated condition ranged up to 10 dB[34]. However, the impact of the substrate's water content on overall A-weighted road traffic noise abatement was predicted to be rather limited (less than 1.5 dBA[34]).

4.TOWARDS INCREASED GREEN ROOF INSERTION LOSS

The numerical and experimental work discussed in Section 3 allows concluding that a flat green roof leads to consistent noise reduction at the non-directly exposed side of a building. However, the insertion loss (relative to a flat rigid roof) is rather limited and on average about 3 dBA for road traffic noise (double diffraction case). It is studied to what extent this mitigation effect can be enhanced by exploring two recent evolutions regarding roof use namely placing solar panels and using shapeable green roofs. The same urban configuration as described in Ref. 30 and the FDTD modeling technique[35] was used in this work as well. This allows to position the current simulations within the large number of simulations already made regarding building envelope greening measures.

4.1.Numerical model

The FDTD technique was used to discretise the sound propagation equations in a non-moving and homogeneous medium:

$$\nabla \cdot p + \rho_0 \frac{\partial \boldsymbol{v}}{\partial t} = \mathbf{0}, \quad (1)$$

$$\frac{\partial p}{\partial t} + \rho_0 c_0^{\,2} \nabla \cdot \boldsymbol{v} = 0. \quad (2)$$

In these equations, p is the acoustic pressure, v is the particle velocity, ρ_0 is the mass density of air, c_0 is the adiabatic sound speed, and t denotes time. Viscosity, thermal conductivity, and molecular relaxation are neglected given the focus on relative effects (insertion losses) of specific measures. A computational grid consisting of both particle velocity components and acoustic pressures (i.e. p-v FDTD[35]) was used with the efficient staggered-in-time and staggered-in-space numerical stencil[35].

The FDTD method is a well-established and validated technique over a wide range of (outdoor) acoustical applications[35]. More information on this model and boundary conditions implementations can be found in related literature[30,35].

4.2.Urban geometry

The geometry under study consists of two coupled urban canyons, 19.2-m wide and 19.2-m high, as shown in Fig. 1. The building connecting the canyons has a width of 9.6 m and a flat roof (similar to case D in Fig. 2 of Ref. 30). Profiled facades have been modeled (by 0.16-m deep recessions due to windows), allowing to capture some diffusion in the canyons to increase realism. Simulations are here performed in two dimensions, implying an infinitely long source and receiver canyon and a coherent line source of infinite length. In Ref. 30, full 3D simulations have been made with a full-wave numerical technique as well, leading to the conclusions that 2D insertion losses of building envelope greening measures are actually quite close to the 3D ones.

The brickwork at the façades is modelled with a frequency-independent reflection coefficient of 0.82[36]. In a conservative approach, this rather low reflection coefficient for bricks is used in order not to overpredict the effectiveness of a measure[30]. The street surface and roofs (non-greened parts) are modelled as rigid. Glass panels (windows) are modelled with a fixed reflection coefficient of 0.975.

Inner-city urban road traffic noise has been assumed. Vehicle speeds vary uniformly between 30 and 70 km/h, with a low fraction of heavy vehicles (5%). Traffic intensity is of no interest in the current study given the interest in traffic noise insertion loss values. Urban traffic in the current street configuration is likely to be composed of multiple lanes. Only considering a single lane (but with multiple source heights, see Fig. 1), compared to multiple sound radiating traffic lanes, did not effect significantly the insertion losses[30]. Sound frequencies were limited to those in the 1.6 kHz-1/3-octave band. Higher frequencies were found not to contribute to A-weighted road traffic noise levels at shielded building facades where the sound field becomes mainly low frequent[18,30].

When presenting numerical results, there is a focus on a single number representation[30]. Receivers are positioned along all non-directly exposed facades (in front of the windows), and along a single line in the courtyard at a receiver height of 1.5 m (see Fig. 1). The difference in A-weighted road traffic noise at each point has been calculated, and this difference is consequently (linearly) averaged over all positions and all vehicles speeds considered.

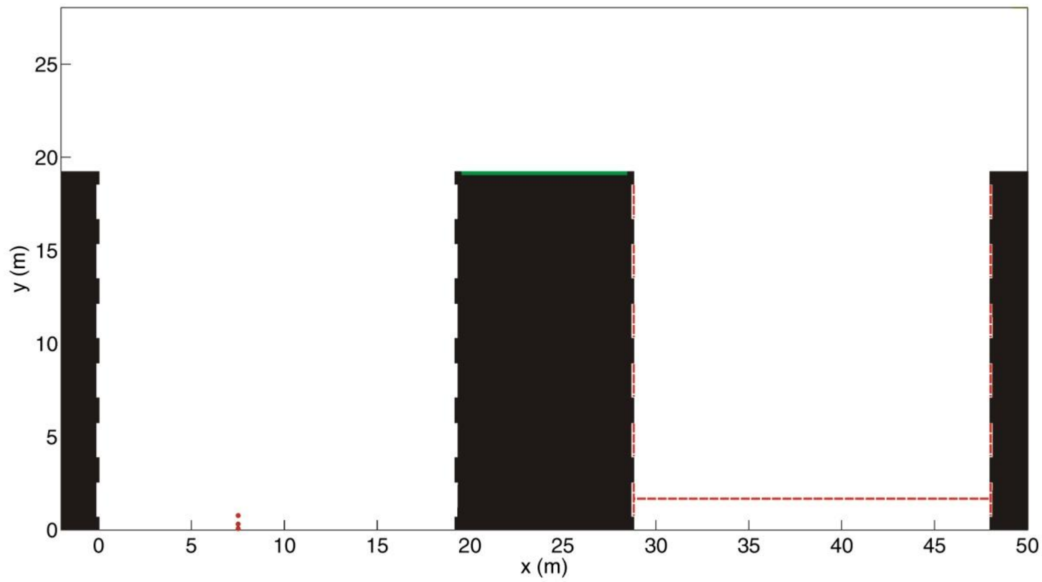

Figure. 1. Urban geometry considered (similar to the one in Ref. 30) to study sound propagation between adjacent city canyons. Receivers are located on all dashed lines in the shielded canyon with a spacing of 2 cm. The green area on top of the central building is the location of the green roof. The 3 dots represent the source positions considered to model road traffic noise.

4.3.Combining solar panels and green roofs

A false conflict with relation to building greening (in a broad sense) is the competition for roof space between green roofs and solar panels. Indeed, recent scientific findings showed that they can mutually enhance the advantages they bring.

Green roofs are able to strongly reduce the roof's surface temperature[19], and contribute to a longer life time of the outer building skin when compared to bare roofs. Solar panels have a negative temperature coefficient, meaning that with increasing surface temperature of the roof, the energy harvesting efficiency decreases. Bringing these two findings together leads to the conclusion that solar panel efficiency increases when placed on a green roof, especially during hot weather. This was experimentally proven[36].

Putting solar panels on a green roof will provide shaded areas. This can actually be an advantage, since shade variations over the roof might increase biodiversity, one of its ecosystem services. Specific plant species are able to colonize shaded zones on roofs[37].

Green roofs have interesting sound absorbing properties as discussed before. Solar panels, in contrast, are acoustically fully rigid. Therefore, a logical question is how solar panels affect sound propagation over a building, and how does this compare to the acoustical performance of a green roof without solar panels. In addition, solar panels are commonly put under an angle making sound diffraction complex. In general, sound waves will propagate not only over the panels, but also underneath them, and at the same time, they will interact with the green roof. A full-wave numerical technique like FDTD, including non-locally reaction modeling of the green roof, is therefore needed.

The green roof substrate considered here is a semi-extensive 10-cm thick limestone-based green roof substrate (60% limestone, 20% loam and 20% organic matter). It has a porosity near 37 % and a density of about 1400 kg/m^3. The measured absorption spectrum can be well approached numerically[30] in FDTD. The measurements underlying the absorption curve were for dry substrates and will thus lead to the maximum possible effect for this type of substrate.

The solar panels are modeled as fully rigid flat plates, with a length of 1 m and a thickness of 6 cm (see Fig. 2a). Given the 2D simulations performed, it is assumed that these are infinitely long as well in the third dimension, or equivalently, a large number of such panels are put in parallel touching their neighbors. Six rows of panels are distributed over the building width as shown in Fig. 3. Inclination angles in between -45° and 45° were modeled. Since details do matter in acoustics, simulations have been performed with and without gaps between the bottom of the panels and the green roof (of 10 cm). For comparison, solar panels on rigid roofs have been simulated as well.

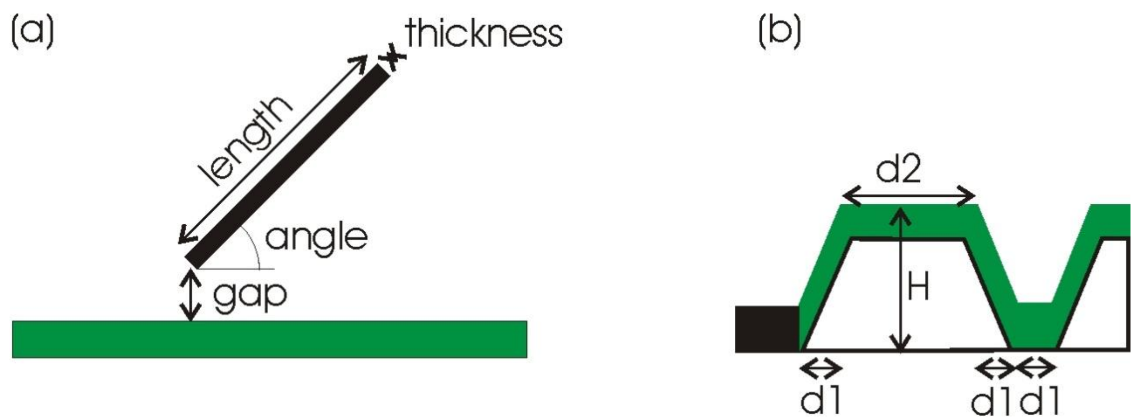

Figure 2. Detail of the solar panels positioned on a green roof (a) and the shaped green roof on hollow trapezium cores (b). The length of the solar panel is 1 m and its thickness 6 cm. The solar panel inclination angles range from -45° to 45°. Negative angles mean that the lowest part of the panel is nearest to the receiving canyon. The trapezium dimensions are d1=0.04 H and d2=0.1 H, with H (the heights of the trapezia) ranging from 0.1 m to 1 m.

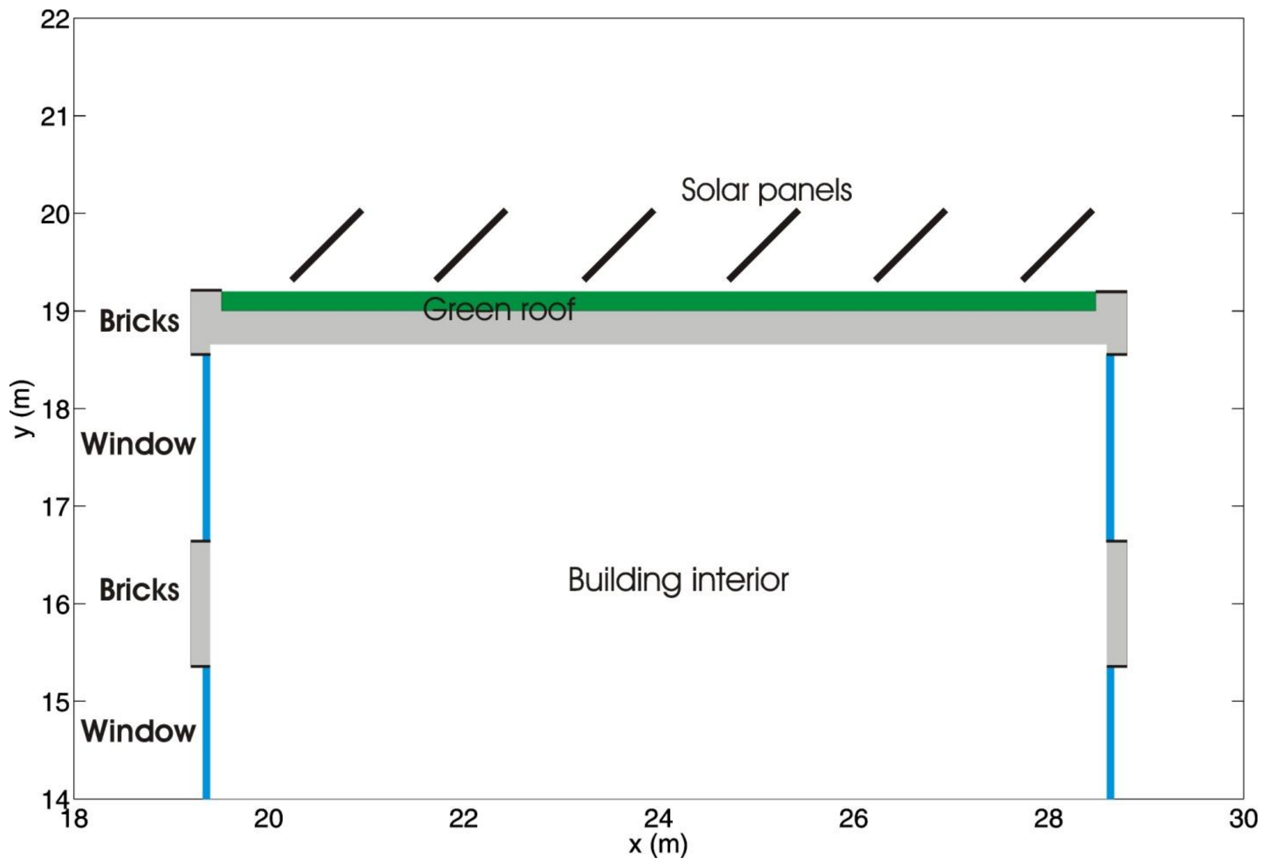

Figure 3. Detail (cross-section) of the central building under study, equipped with a green roof and 6 rows of solar panels under an angle of 45°**.**

In case there are gaps in between the bottom of the solar panels and the green or rigid roof, the addition of the panels generally give positive but small overall road traffic noise reduction (see Table 1). However, at some lower inclination angles, very small negative effects are predicted as well, which would mean that the presence of the panels leads to somewhat larger exposure levels (on average) along the shielded zone. With increasing angle (in the range considered), the (positive) effect becomes somewhat larger. The solar panel insertion loss of a green flat roof and rigid flat roof is more or less similar. This means that the panels do not facilitate additional interaction between the sound waves and the green roof.

Table 1. Predicted solar panel insertion losses (in dBA) for various panel inclinations, averaged over all receivers in the shielded canyon, for urban road traffic.

		solar panel inclination					
Reference situation		**-45°**	**-30°**	**-15°**	**15°**	**30°**	**45°**
Rigid flat roof	gap	0.9	-0.3	0.0	0.0	-0.1	0.9

	no gap	3.6	1.4	0.5	0.7	1.7	3.9
Flat lime-stone green roof	gap	0.9	0.4	-0.3	-0.3	0.3	0.9
	no gap	5.6	4.1	1.8	1.8	4.2	5.7

In case the solar panels touch the green roof (no gaps at their bottoms), only positive and much larger effect are predicted relative to the absence of panels. Direct shielding by the solar panels plays a role, since significant noise reduction is predicted for both a rigid roof and a flat green roof, and since the insertion losses increase with angle. In addition, the (averaged) insertion loss spectra shown in Fig. 4 suggest that periodicity effects[39,40] contribute to the sound pressure level reduction. The somewhat decreased efficiency at very low frequencies (below 50 Hz), especially for the 45° solar panel inclination, are most likely due to surface waves[41] generated by the periodic spacing of the solar panels on the roof. Already starting near the engine noise frequency range, a strong enhancement in noise reduction is obtained, leading to a positive overall effect for A-weighted road traffic noise.

The solar panel (no gaps) insertion loss of the flat green roof turns out to be larger now than the one of the rigid flat roof (see Table 1). The interaction between the sound waves and the absorption the green roof provides leads to stronger road traffic noise reduction.

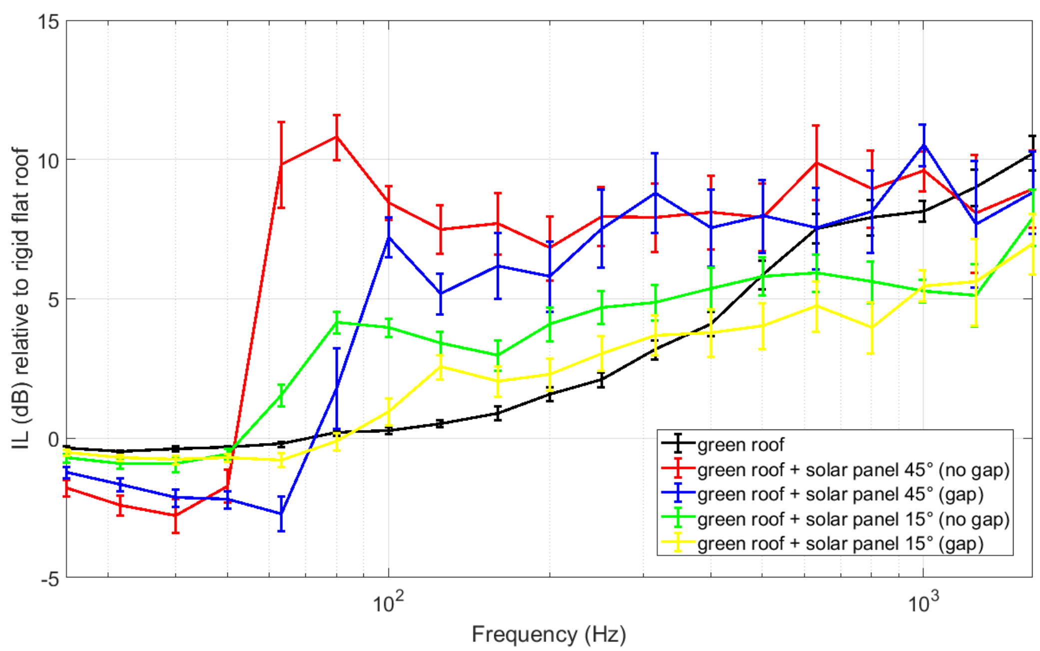

Fig. 4. Insertion loss spectra averaged over all receivers (see Fig. 1), for two solar panel inclinations, with or without gaps. The error bars have a total length of two times the standard deviations and were calculated for each 1/3-octave band separately. For comparison, the green roof insertion loss spectrum (in absence of solar panels) is depicted as well.

When there are gaps, a large portion of the acoustical energy still propagates underneath it and thus strongly lowers its noise reducing potential. The sound propagation situation turns out to be quite symmetrical: the angle itself is much more important than the direction the panel is facing (either towards the source canyon or receiver canyon).

The insertion loss of the limestone green roof (without solar panels), relative to a rigid flat roof, is 2.1 dBA (in 2D)[30] and 2.4 dBA (in 3D)[30]. For a 45-degree inclination, with the solar panels directed towards the receiving canyon, in total 7.8 dBA (in 2D) road traffic noise reduction is obtained with the combination green roof and solar panel, relative to a rigid flat roof. This means that a significant decrease in sound exposure level along the shielded zone is predicted.

4.4.Shapeable green roofs

New types of green roofs have emerged in recent years, like e.g. green roof substrate made of hydrophilic polyurethane (PUR) foam. Such a material, injected with fertilizer, can serve as a substrate for many plant species, amongst them also sedum. Benefits are the large water buffer capacity, their light weight and good thermal insulation. In addition, a single slab of such a material can replace the various layers typically used in a green roof system; grooves at the bottom serve as a water evacuation layer. This means that such a material is easily put in place on a roof. Another advantage is that this material can be shaped to almost any form, which opens possibilities for increased sound reduction. Literature shows that in case of near-grazing sound propagation, scattering of sound at irregularities could make rigid materials behave acoustically softer[38]. It is numerically explored how such a material can be used to optimize road traffic noise reduction at a quiet side.

The measured absorption spectrum of a 6-cm thick (dry) slab of such a green roof substrate foam is depicted in Fig. 5. The porosity of the substrate is equal to 98 %, the density is 33 kg/m^3 and the material has a water buffer capacity of 70 % of its own volume. The PUR substrate provides a much lower absorption at low sound frequencies than the lime-stone based granular substrate considered here. However, at higher frequencies, full absorption is reached.

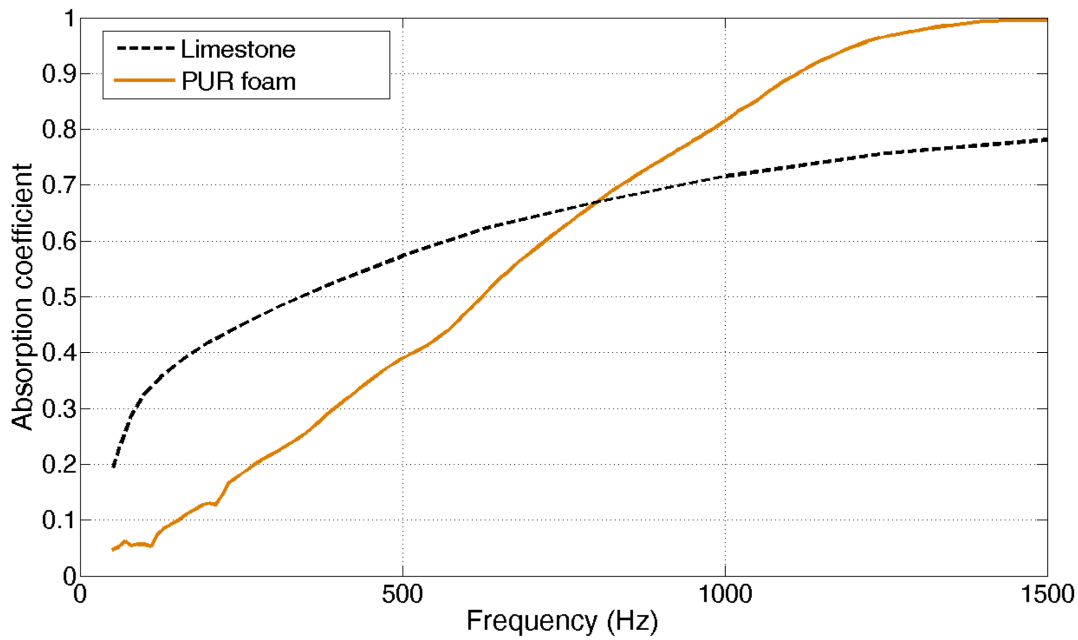

Figure 5. Measured absorption coefficient spectra of the green roof substrate types under study (dry conditions).

A simulation is made for a single slab of this material placed on a flat roof. The insertion loss is predicted to be only 0.9 dBA relative to a rigid flat roof, which is much lower than the noise reduction one obtains for the lime-stone based green roof (2.4 dBA relative to a rigid flat roof). Note that the sound field in the shielded canyon is dominated by the low-frequency range. The poorer absorption performance below 500 Hz makes this material not suitable to achieve noise reduction in such an application.

In a next step, it is studied to what extent placing such flexible green roof slabs on trapezium-shaped hollow cores influence sound diffraction. The use of such hollow cores could increase the interaction between sound waves and the material. A full pack of such a material, in contrast, could lead to an impractical situation due to the excessive weight on the roof structure after long periods of rainfall.

Trapezia of various heights have been considered, starting from 10 cm. The dimensions are proportionally adapted on their height as shown in Fig. 2b. Only an integer number of trapezia have been considered in this work, the remaining part of the roof is covered with a flat green roof of the same material. The maximum trapezium height considered is 1 m. A cross-section for a trapezium height of 0.5 m is shown in Fig. 6.

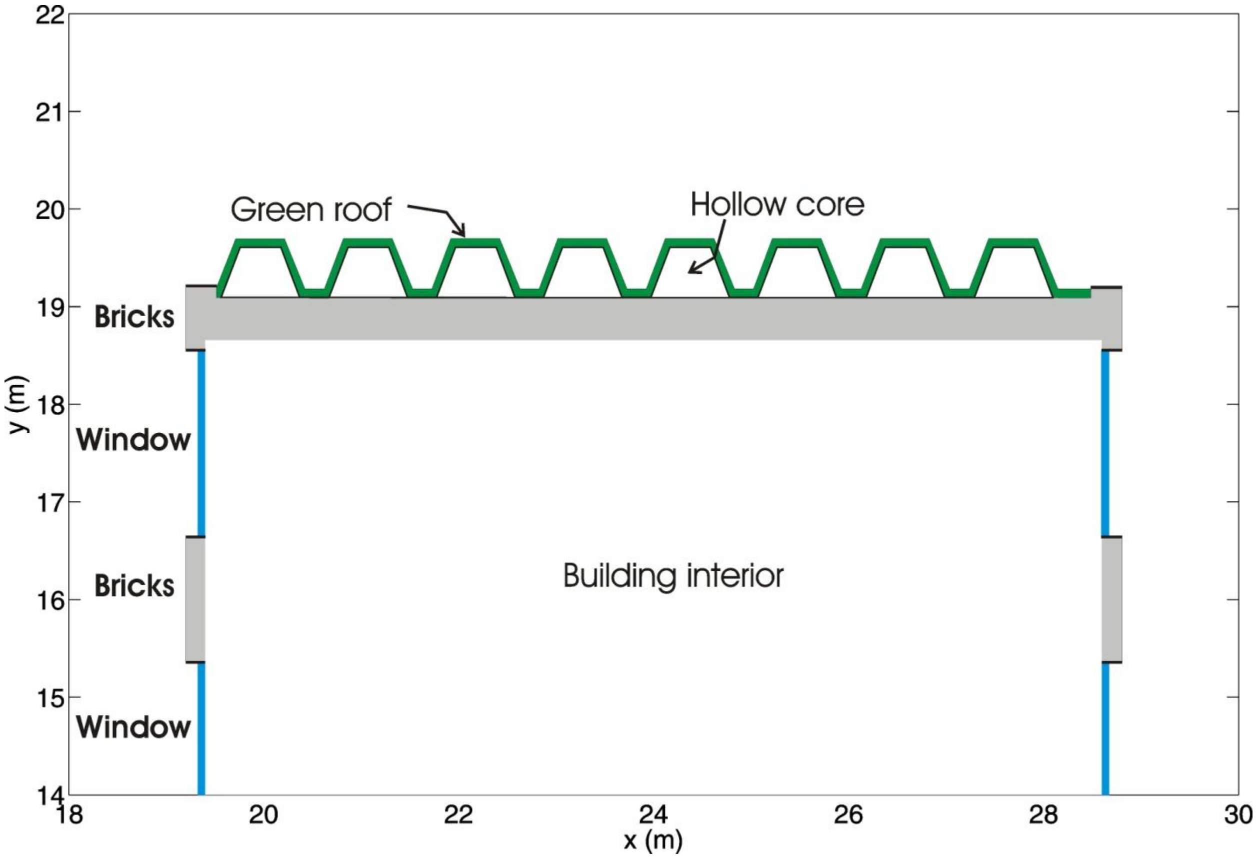

Figure 6. Detail (cross-section) of the central building under study, equipped with slabs of PUR foam green roof substrates on hollow trapezium cores (here, the trapezium height H equals 0.5 m).

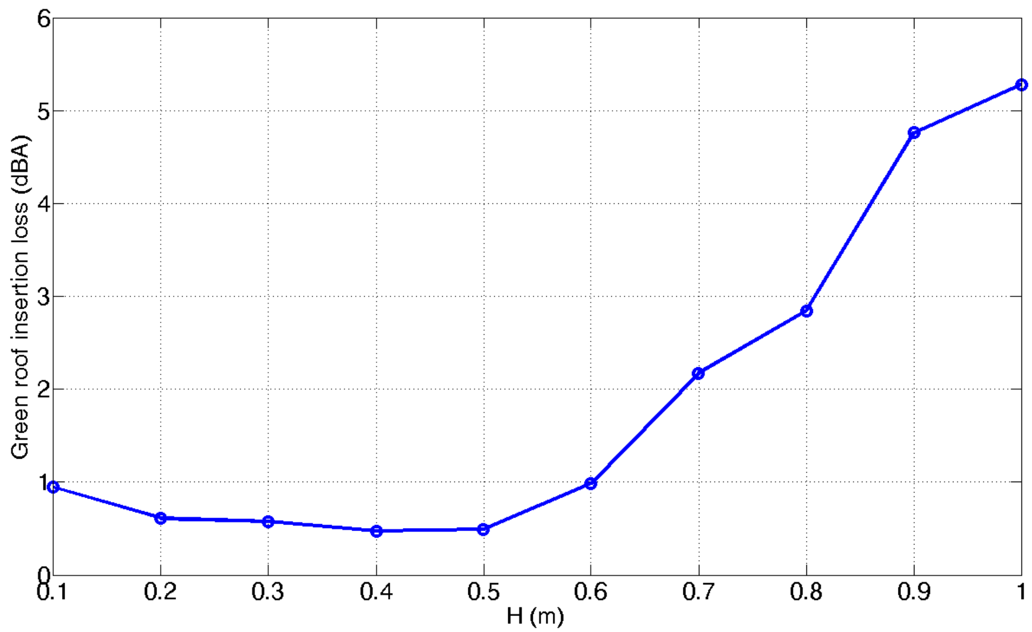

Figure 7. Predicted insertion losses of PUR foam green roof slabs placed on hollow trapezium-like cores of various heights. Averaged insertion losses, relative to rigid flat roofs, in the shielded canyon for urban road traffic, are shown.

Only above 0.5 m, as shown in Fig. 7, increasing trapezium height leads to an increase in green roof insertion loss. For a trapezium height of 1 m, which is still reasonably small relative to the total building height of 19.2 m, an insertion loss relative to a rigid flat roof exceeding 5 dBA is predicted. This is a significant improvement of the shielding by a rigid flat roof and also by a flat PUR green roof (which gave less than 1 dBA). Note that this shaping hardly increases the weight load on the roof. The efficiency of a 10-cm thick lime-stone substrate is exceeded in this specific urban setting once a trapezium height of 0.8 m is reached.

5.CONCLUSIONS

Flat green roofs were shown to provide roughly 3 dBA urban road traffic noise reduction relative to a common flat rigid roof. This is concluded based on numerical simulations and a few real-life case studies reported in literature. It has been explored in this work how this shielding can be further increased in case of flat roofs.

Solar panels should be used in tandem with green roofs. Besides increased biodiversity on the roof and higher solar energy harvesting efficiency during hot periods, such panels are also predicted to increase noise shielding. With increasing inclination angle and especially when there are no gaps between the bottom of the panels and the green roof, positive effects become more pronounced. For a 45° inclination angle, more than 5 dBA additional road traffic noise reduction is theoretically predicted by the presence of the solar panels (placed on a lime-stone based 10-cm thick green roof). This effect is the result of direct shielding by the panels, periodicity effects and the enhanced interaction between the sound waves diffracting over the roof and the absorption provided by the green roof (substrate).

Shapeable polyurethane green roof slabs provide poor absorption below 500 Hz. Given that the sound field behind a building is dominant low frequent, a direct application on a flat roof yields an averaged effect of less than 1 dBA in the shielded zone. When placing on trapezium-like hollow cores on the (flat) roof, shielding efficiency can be strongly enhanced. For a 1-m high trapezium core placed on a 19.2-m high building, the shielding efficiency relative to a rigid flat roof is predicted to exceed 5 dBA on average. Note that such slabs have a low weight and are easily manageable. So this is still a practical solution with no additional weight constraints for the roof structure.

The improvements predicted in this work, relative to flat rigid roofs, are significant at the non-directly exposed side of a building in a (dense) urban setting. At such locations, exposure levels can easily range up to 50 dBA[13]. These level reductions could therefore help in achieving a (true) quiet building side (<45 dBA[13]) and a corresponding decrease in the percentage sleep disturbed or noise annoyed dwellers.

REFERENCES

1. Heutschi K. A simple method to evaluate the increase of traffic noise emission level due to buildings, for a long straight street. *Appl Acoust* 1995; 44:259–274.

2. Thomas P, Van Renterghem T, De Boeck E, Dragonetti L, Botteldooren D. Reverberation-based urban street sound level prediction. *J Acoust Soc Am* 2013; 133:3929-3939.

3. Jean P. Sound transmission through opened windows. *Appl Acoust* 2009; 70:41–49.

4. Locher B, Piquerez A, Habermacher M, Ragettli M, Röösli M, Brink M, Cajochen C, Vienneau D, Foraster M, Müller U, Wunderli J. Differences between outdoor and indoor sound levels for open, tilted, and closed windows. *Int J Environ Res Public Health* 2018; 18:15.

5. Lyon R. Role of multiple reflections and reverberation in urban noise propagation. *J Acoust Soc Am* 1974; 55:493–503.

6. Kang J. Sound propagation in street canyons: Comparison between diffusely and geometrically reflecting boundaries. *J Acoust Soc Am* 2000; 107:1394–1404.

7. Ismail M, Oldham D. A scale model investigation of sound reflection from building facades. *Appl Acoust* 2005; 66:123–147.

8. Picaut J, Scouarnec D. Using acoustic diffusors to reduce noise in urban areas. *Act Acust Acust* 2009; 95:653-668.

9. Echevarria-Sanchez G, Van Renterghem T, Thomas P, Botteldooren D. The effect of street canyon design on traffic noise exposure along roads. *Build Env* 2016; 97:96-110.

10. Van Renterghem T, Salomons E, Botteldooren D. Parameter study of sound propagation between city canyons with coupled FDTD-PE model. *Appl Acoust* 2006; 67:487-510.

11. Hornikx M, Forssen J. A scale model study of parallel urban canyons. *Act Acust Acust* 2008; 94:265-281.

12. Hornikx M, Forssen J. Noise abatement schemes for shielded canyons. Appl Acoust 2009, 70:267-283.

13. Öhrström E, Skånberg A, Svensson H, Gidlöf-Gunnarsson A. Effects of road traffic noise and the benefit of access to quietness. *J Sound Vib* 2006; 295:40–59.

14. Klæboe R. Are adverse impacts of neighbourhood noisy areas the flip side of quiet area benefits? *Appl Acoust* 2007; 68:557–575.

15. de Kluizenaar Y, Salomons E, Janssen S, van Lenthe F, Vos H, Zhou H, Miedema H, Mackenbach J. Urban road traffic noise and annoyance: The effect of a quiet façade. *J Acoust Soc Am* 2011; 130:1936-1942.

16. Van Renterghem T, Botteldooren D. Focused study on the quiet side effect at dwellings highly exposed by road traffic noise. *Int J Environ Res Public Health* 2012; 9:4292-4310.

17. Bodin T, Björk J, Ardö J, Albin M. Annoyance, Sleep and Concentration Problems due to Combined Traffic Noise and the Benefit of Quiet Side. *Int J Environ Res Public Health* 2015; 12:1612-1628.

18. Van Renterghem T, Botteldooren D. The importance of roof shape for road traffic noise shielding in the urban environment", T. Van Renterghem, D. Botteldooren. *J Sound Vib* 2010; 329:1422-1434.

19. Perez G, Perini K (eds.). *Nature based strategies for urban and building sustainability*. Oxford-Cambridge: Elsevier, 2018.

20. Connelly M, Hodgson M. Experimental investigation of the sound transmission of vegetated roofs. *Appl Acoust* 2013; 74:1136–1143.

21. Galbrun L, Scerri L. Sound insulation of lightweight extensive green roofs. *Build Env* 2017; 116:130-139.

22. Connelly M, Hodgson M. Experimental investigation of the sound absorption characteristics of vegetated roofs. *Build Env* 2015; 92:335-346.

23. Embleton T. Tutorial on sound propagation outdoors. *J Acoust Soc Am* 1996; 100:31-48.

24. Horoshenkov K, Khan A, Benkreira H. Acoustic properties of low growing plants. *J Acoust Soc Am* 2013; 133:2554–2565.

25. Ding L, Van Renterghem T, Botteldooren D, Horoshenkov K, Khan A. Sound absorption of porous substrates covered by foliage: experimental results and numerical predictions. *J Acoust Soc Am* 2013; 134:4599-4609.

26. Nilsson M, Bengtsson J, Klæboe R (eds.). *Environmental Methods for Transport Noise Reduction*. Boca Raton, US: CRC Press, Taylor & Francis Group, 2015.

27. Attal E, Cote N, Haw G, Pot G, Vasseur C, Shimizu T, Granger C, Croënne C, Dubus B. Experimental characterization of foliage and substrate samples by the three-microphone two-load method. Proceedings of Internoise 2016, Hamburg, Germany.

28. Van Renterghem T, Botteldooren D. Numerical evaluation of sound propagating over green roofs. *J Sound Vib* 2008; 317:781-799.

29. Van Renterghem T, Botteldooren D. Reducing the acoustical façade load from road traffic with green roofs. *Build Env* 2009; 44:1081-1087.

30. Van Renterghem T, Hornikx M, Forssen J, Botteldooren D. The potential of building envelope greening to achieve quietness. *Build Env* 2013; 61:34-44.

31. Van Renterghem T, Botteldooren D. In-situ measurements of sound propagating over extensive green roofs. *Build Env* 2011; 46:729-738.

32. Van Maercke D, Defrance J, Maillard J, Anselme C, Mandon A, Altreuther B, Smyrnova Y, Van Renterghem T, Jeon J-Y, Jang H-S, Kim Y-H. Holistic acoustic design and perceptual evaluation : Case studies and data collection, technical report, the HOSANNA project, 2013.

33. Jeon J-Y, Jang H-S, Kim Y-H. Examine and quantify the acoustic effectiveness of vegetation in urban spaces through 1:10 scale model, technical report, the HOSANNA project, 2013.

34. Van Renterghem T, Botteldooren D. Influence of rainfall on the noise shielding by a green roof. *Build Env* 2014; 82:1-8.

35. Van Renterghem T. Efficient outdoor sound propagation modeling with the finite-difference time-domain (FDTD) method: a review. *Int J Aeroacoust* 2014; 13:385-404.

36. ISO9613-2. *Acoustics : attenuation of sound during propagation outdoors (part 2)*. Geneva, Switzerland: International Organisation for Standardisation, 1996.

37. Schindler B, Blank L, Levy S, Kadas G, Pearlmutter D, Blaustein L. Integration of photovoltaic panels and green roofs: review and predictions of effects on electricity production and plant communities. *Israel J Ecol Evol* 2016; 62:68-73.

38. Boulanger P, Attenborough K, Taherzadeh S, Waters-Fuller T, Li K M. Ground effect over hard rough surfaces. *J Acoust Soc Am* 1998; 104:1474-1482.

39. Bashir I, Hill T, Taherzadeh S, Attenborough K, Hornikx M. Reduction of surface transport noise by ground roughness. *Appl Acoust* 2014; 83:1-15.

40. Van Renterghem T, Taherzadeh S, Hornikx M, Attenborough K. Meteorological effects on the noise reducing performance of a low parallel wall structure. *Appl Acoust* 2017; 121:74-81.

41. Donato R. Model experiments on surface waves. *J Acoust Soc Am* 1978; 63:700-703.

TABLE

Table 1. Predicted solar panel insertion losses (in dBA) for various panel inclinations, averaged over all receivers in the shielded canyon, for urban road traffic.

		solar panel inclination					
Reference situation		**-45°**	**-30°**	**-15°**	**15°**	**30°**	**45°**
Rigid flat roof	gap	0.9	-0.3	0.0	0.0	-0.1	0.9
	no gap	3.6	1.4	0.5	0.7	1.7	3.9
Flat lime-stone green roof	gap	0.9	0.4	-0.3	-0.3	0.3	0.9
	no gap	5.6	4.1	1.8	1.8	4.2	5.7

FIGURE CAPTIONS

Figure. 1. Urban geometry considered (from Ref. 30) to study sound propagation between adjacent city canyons. Receivers are located on all dashed lines in the shielded canyon with a spacing of 2 cm. The green area on top of the central building is the location of the green roof. The 3 dots represent the source positions considered to model road traffic noise.

Figure 2. Detail of the solar panels positioned on a green roof (a) and the shaped green roof on hollow trapezium cores (b). The length of the solar panel is 1 m and its thickness 6 cm. The solar panel inclination angles range from -45° to 45°. Negative angles mean that the lowest part of the panel is nearest to the receiving canyon. The trapezium dimensions are d1=0.04 H and d2=0.1 H, with H (the heights of the trapezia) ranging from 0.1 m to 1 m.

Figure 3. Detail (cross-section) of the central building under study, equipped with a green roof and 6 rows of solar panels under an angle of 45°.

Fig. 4. Insertion loss spectra averaged over all receivers (see Fig. 1), for a few solar panel inclinations, with or without gaps. The error bars have a total length of two times the standard deviations and were calculated for each 1/3-octave band separately. For comparison, the green roof insertion loss spectrum (no solar panels) is depicted as well.

Figure 5. Measured absorption coefficient spectra of the green roof substrate types under study (dry conditions).

Figure 6. Detail (cross-section) of the central building under study, equipped with slabs of PUR foam green roof substrates on hollow trapezium cores (here, the trapezium height H equals 0.5 m).

Figure 7. Predicted insertion losses of PUR foam green roof slabs placed on hollow trapezium-like cores of various heights. Averaged insertion losses, relative to rigid flat roofs, in the shielded canyon for urban road traffic.