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Effects of urban morphology on traffic noise: A parameter study including indirect noise exposure and estimated health impact

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ABSTRACT

Noise exposure has been calculated and analysed for 31 different urban morphologies in an urban setting. For five of the urban morphologies also vegetation surfaces on facades and roofs were studied. Facade exposures were analysed for both smaller (single-sided) flats and larger (floor-through) flats, considering the direct exposure from the roads as well as the indirect exposure at noise-shielded positions like inner yards. Also, grid map area exposures at ground level were calculated and analysed for both sidewalk and yard areas. The facade exposure levels, using indicators Lden and Lnight, were used to estimate annoyance and sleep disturbance as well as disease burden in terms of DALY (Disability-Adjusted Life Years) per person. In all urban morphology cases, single-sided flats showed overall better performance (i.e. lower DALY) than larger, floor-through flats; however, the inclusion of a bonus for additional facade elements having a lower noise exposure gave the large flats a similar or better predicted overall performance compared with the small flats. Among the building types studied, for small flats and constant building density, the use of perimeter blocks with closed inner yards, slightly open yards and U-shaped buildings showed results of relatively better overall performance compared with I-shaped, L-shaped and point buildings. When the yards grow in size, the performance of closed inner yards dropped. As general trends, perimeter blocks were shown to perform better than morphologies with less enclosed yards and densification with constant traffic flow was shown to result in improved performance. However, building types with slightly open yards may provide an attractive compromise solution due to its relatively good noise shielding at the same time as enabling solutions to air pollution and corner-flat layouts. In addition, complementing the perimeter blocks with towers was shown to enable improvement. Furthermore, traffic concentration by locating all local traffic to a single road was shown to be beneficial, increasingly so by widening the road. Predicted effects of vegetation surfaces on facades and roofs showed significant overall improvement, where closed inner yards benefit from vegetated roofs. The area exposure results showed that when the building blocks are successively less enclosed the levels are reduced on the sidewalks and increased in the yards. Also, the benefit of facade vegetation is shown for the area exposures.

1. Introduction

Outdoor noise in urban areas causes reduced quality of life for the inhabitants. For example, in Europe, it has been estimated that more than 20 % of the population is exposed to environmental noise at harmful levels, using the day-evening-night noise level (L_{den}) limit value 55 dB [1]. Within the part of the population exposed above 55 dB (L_{den}), it is estimated that more than two thirds live inside urban areas, for which road traffic is by far the dominating source [1].

It is well-established that there is a strong link between urban planning and sound environment (e.g. [2]). It is also well-known that, within the context of urban planning, urban morphology has an impact on the noise exposure. That is, the configuration and disposition of buildings in relation to the noise sources, e.g. the roads, can have a large effect on the noise levels at the building facades and at inner yards (e.g. [3–12]). The present paper presents a systematic parameter study of varying morphologies where noise

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exposure from road traffic is calculated and analysed. Besides the impact on varying morphologies, the paper looks at the role of density (floor space index, i.e. floor area ratio), one of the included parameters, on noise exposure. Also, effects of vegetated roofs and facades are studied. In order to compare the noise impact of the different cases studied, a quantitative comparison using a single-number indicator is preferable. For this purpose, the DALY measure (Disability-Adjusted Life Year) is used here, as based on [13,14].

The benefits in human wellbeing when apartments have access to a less noisy side (mostly in terms of perceived annoyance but also in terms of self-reported sleep disturbance and other health-related responses), has been investigated previously, mainly in the two projects *Soundscape Support to Health* (see e.g. [15]) and *Qside* (see e.g. [16]). The results from the former show that access to a *quiet facade* ($L_{Aeq,24h} \leq 45$ dB free field value with the association + 3 dB, 2 m from the facade) can be modelled as a bonus of 5 dB to the noise level on the directly exposed facade [15], whereas the results from the latter indicate for a model where the bonus is proportional to the difference in noise level between most and least exposed sides [16]. Short reviews about the benefit of access to relative quietness can be found in Refs. [17], Ch. 5.1.3] and [18]].

For improved prediction accuracy for the less exposed facade elements, e.g. at closed inner yards, the noise exposure is here calculated using a combination of a commercially available noise mapping software and an in-house extension for inner yards, as described previously [19]. The noise indicators considered here are limited to A-weighted equivalent levels $L_{Aeq,24h}$, L_{den} and L_{night}, which is coherent with the DALY estimation for noise since these are based on L_{den} and L_{night}.

The work presented here is part of a project encompassing both air pollution and noise exposure, whereas the current paper focuses on noise only.

2. Method

2.1. Model cases of urban morphology

To investigate effects of urban morphology on noise exposure, the spacematrix method has been shown useful for daylight exposure [20] and for traffic noise distribution [21]. Spacematrix is a method to describe urban morphologies parametrically and consists of a three-dimensional coordinate system that allows for a comparison of the variable values for buildings of different forms. The coordinate system is set up as follows. The floor space index, FSI, on the *y*-axis, ground space index, GSI, on the *x*-axis and network density, N, on the *z*-axis. Further variables of the diagram are open space ratio, OSR, and number of floors, L.

GSI describes the building coverage of the site area: GSI = F/A, where F (m^2) is the building footprint and A (m^2) is the area of the site (which here equals 201 535 m^2 for all cases). FSI describes the relation between the total gross floor area, GFA (GFA = F·L), and the site area: FSI = GFA/A. Network density, N (m^{-1}), describes the length of streets per site area: N = S/A, where S (m) is the total street length of the area (where the streets enclosing the site are counted half). Furthermore, OSR can be derived from the variables FSI and GSI and is calculated as OSR = (1-GSI)/FSI (e.g. [16], pp. 107–111]]). The building height, H, is here taken as H = 3.5L + 1.5 (m) where all buildings have flat roofs.

Urban morphologies span over separate regions of the spacematrix, which allows the study of, on the one hand, well-known building types such as perimeter block buildings and point buildings and, on the other hand, the role the separate variables have on the performance, in this case noise exposure.

The 31 different morphologies used here include seven distinct building types: perimeter blocks with fully enclosed yards (denoted as closed yards, CY), U-shaped blocks (UB), perimeter blocks with open corners (OC), slab buildings (I-shaped blocks, IB), L-shaped blocks (LB) and point buildings that are positioned in the centre of the plot (PC) or along the road without setback (PR). (See Fig. 1, upper half.) The GSI values decrease in order of building types CY, UB, OC, IB, LB, PR and PC which results in morphologies with less enclosed yards. FSI values decrease accordingly if building height is kept constant. A lower FSI may have negative consequences for the economic feasibility of a project and might also influence the level of service that can be provided because increased built coverage (i.e. GSI) and built intensity (i.e. FSI) tend to influence urban vitality positively, other things being equal [22].

Building type CY is chosen as base type and results are presented with this as reference. The building types are positioned in a real urban setting (see Fig. 2) and have a fixed traffic volume of 1500 average daily traffic (ADT) in the new streets (whereof 5 % are medium heavy and 5 % are heavy vehicles) driving 50 km/h, while official data are used for the existing streets that surround the model area.

To systematically investigate the role of the building types and the associated variable values, the study freezes one variable at a time to test the impact of the other ones. For the seven distinct building types above, one series is investigated when FSI is constant and L varies, while in the other series L is constant and FSI varies.

For the base type, CY, we further investigate the impact of block size (and thus network density, N), street width (of one street, increased from the base value 20 m to 40 m and 80 m) and the addition of towers to perimeter buildings blocks (along one street). (See Fig. 1, lower half.) When the block size increases and the number of streets decreases, the traffic volumes are adjusted to keep the total volume in the area constant. In addition, the cases with varying width of the main street are tested both with equally distributed traffic in all streets and with a concentration of all traffic to the main street, while the other streets are closed for motorised traffic, referred to as boulevardisation cases. The total traffic volume in the main street is in those cases 9000 instead of 1500 (ADT). Also, the increase of number of floors for the base type (CY) is investigated, varying from 5 floors to 8 and 12 floors. The parameter values for all cases, including variations in building height (number of floors) are summarised in Table 1. (Note that due to that the number of floors here is an integer value, the FSI constant series allow some variation in actual FSI values around the ideal FSI value.)

The cases include 8 series and are given IDs from 1.1 to 8.3. Further, the role of vegetation on buildings (facades and roofs) for noise exposure are investigated for building types CY and OC as well as for the boulevardisation cases (Cases 7.1–7.3). In addition to keeping the traffic flow constant within the model area, an extra set of calculations was made for the buildings of Series 2 but where the traffic flow was allowed to change with population, i.e. proportionally with FSI (denoted '2 Tr' in Table 1).

2.2. Prediction of noise exposure

The noise exposure is calculated using a combination of a commercially available noise mapping software (Soundplan, version 8.0) and an in-house extension for inner yards [23] based on results from the Qside project [24]. The combined methodology, implemented in Matlab, is described in [19].

When the sound propagation from road vehicles to the nearest facade is unshielded, the noise level is usually dominated by this direct exposure. The indirect noise exposure, on the other hand, typically becomes significant for shielded inner yards, where recei-

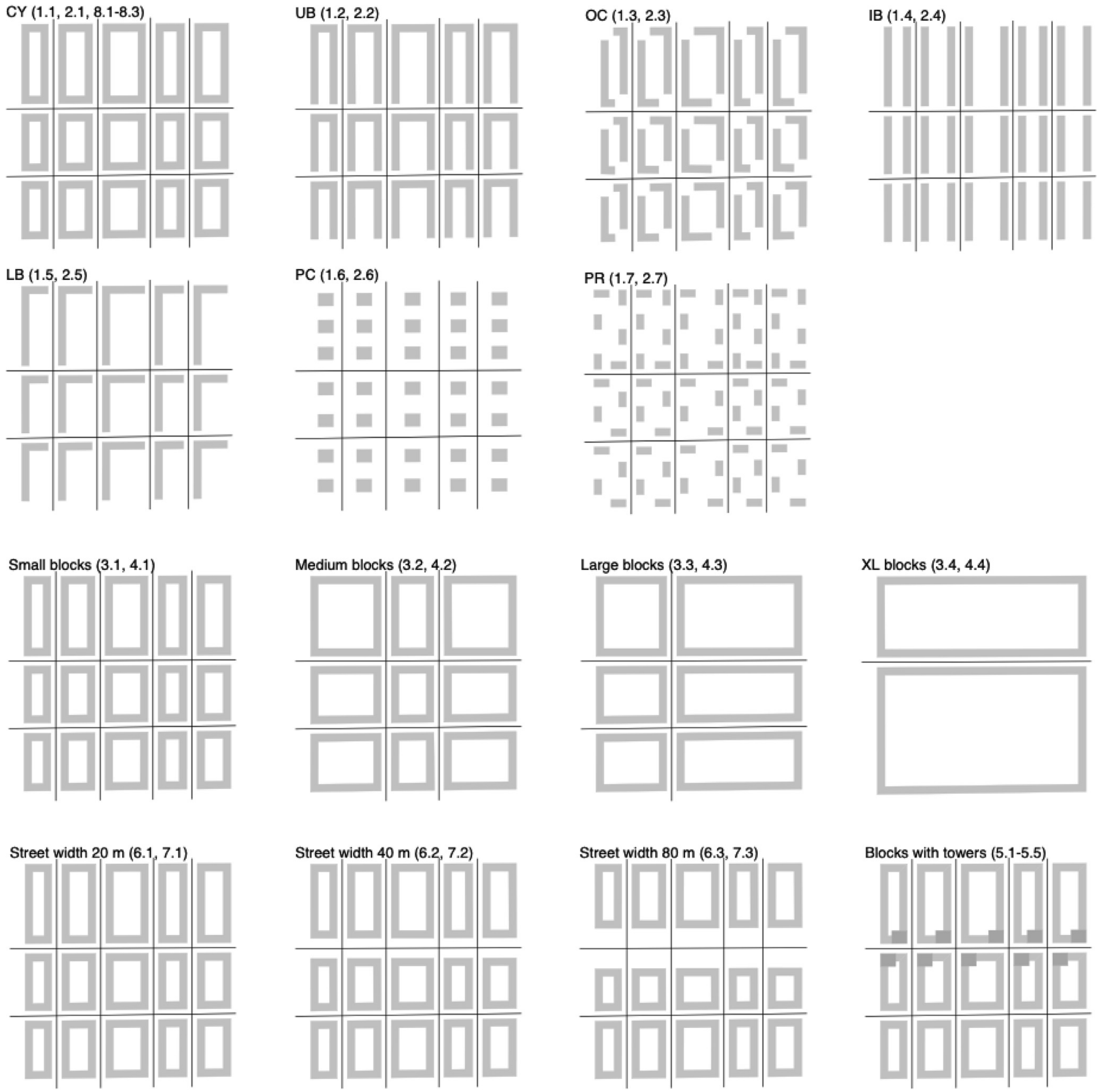

Fig. 1. Top view of the model area for all cases: buildings (grey areas) and roads (black lines marking the road centre lines).

ver positions do not have unobstructed paths from the sources. The noise level at such positions may be dominated by sound paths over the roofs, including multiple reflections in the street canyon and/or in the inner yard (see e.g. [25]), as is here predicted using an implementation of the model from the Qside project [19,23,26,27]. This engineering model, in the following denoted the indirect noise model, was originally developed using analytical models in combination with results from wave-based numerical predictions and multiple measurements [24], thereafter further updated [19]. The geometric input to the indirect noise model contains information on the building heights, both in the street space and in the yard, as well as positions of source and receiver and the width of the intermediate building. A correction for non-flat roofs (ridge roof) is available, the facade reflection coefficient can be varied and the model provides output as function of frequency [24]. It is well established that a simplified application of standard noise mapping models to shielded inner yards may result in large underestimations, with errors of 10 dB or more not being uncommon [6,23,19].

The calculations are made for the third-octave bands 25–10 000 Hz. In the noise mapping software the Nord2000 Road prediction model is used, with five reflections and neutral weather condition. The final results from the noise mapping software and from the indirect noise model are A-weighted to single number levels from which the maximum of the two is used as the final result at each point, applied to both facade levels and grid noise maps (receiver height 2 m).

The above-described combined approach has previously been described and tested in [19]. Whereas evaluations of established noise mapping models are plentiful (see e.g. [28,29]), the

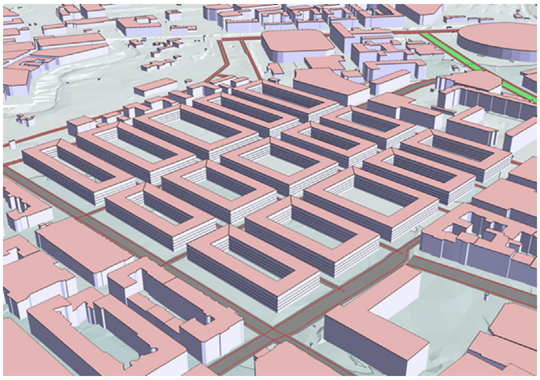

Fig. 2. 3D view of the urban area where the model cases are located, exemplified for the building type CY with five floors (i.e. Case 1.1).

validations of indirect noise prediction models are more scarce; the model used here has been validated for a few cases (see [23,24]) whereby the applicability for the full range of possible cases, e.g. varying the facade absorption, could be more substantiated.

The effects of vegetation surfaces on facades and roofs are investigated for Cases 1.1, 1.3 and 7.1–7.3. For Case 1.3, the vegetation treatment is given to all facades whereas for the other cases, with closed yards, vegetation treatment is limited to be on facades toward the road. All surface coverage of facade vegetation is limited to floors above the ground floor. The effect of facade vegetation is modelled in the noise mapping software using a frequency dependent acoustic absorption assuming a 200 mm thick substrate covering 80 % of the surface, assuming a 20 % window area [30]. The effect of vegetated roofs is modelled using a frequency dependent insertion loss (in dB) within the indirect noise level calculation. The insertion loss values are based on previous numerical modelling [31], extrapolated from calculation results for flat roofs. The values used here of facade absorption coefficient and green roof insertion loss are listed in Table 2.

For calculation purposes it should be noted that the grid noise map values include facade reflections whereas the facade noise levels are given as free field values, i.e. estimating the level as if the last reflection in the same facade is omitted. For an energy-based noise mapping model, a reflection would typically contribute by about 2 dB, resulting from an energy doubling (3 dB) minus a reflection loss of 1 dB for a typical facade absorption model as assumed here [32]. The indirect noise model estimates the level including reflections and a subtraction of 2 dB is used here to convert to the free field level as predicted by the noise mapping software, following the above reasoning.

The single number levels calculated here are values of the $L_{Aeq,24h}$ indicator. Using standard values for 24-hour road traffic distributions for urban roads [33], conversions to the L_{den} and L_{night} indicators have been estimated as:

$$L_{den} = L_{Aeq,24h} + 3.5 \text{ (dB)}$$

$$L_{night} = L_{Aeq,24h} - 5.4 \text{ (dB)}.$$

2.3. Modelling of noise exposure with and without quiet-side bonus

To model the noise exposure for the residents in the buildings, based on the facade noise levels, two variants of apartment layouts were used, denoted as *small flats* and *large flats*. For the small flat layouts, most apartments are single-sided whereas for the large flat layouts, there are mostly floor-through apartments, in the sense that they extend from the front of the building to the rear of the building. An algorithmic approach for automatically creating the apartment layouts was implemented, for which results are exemplified in Fig. 3.

It should be noted that the automated layouts show some apartment solutions that for a real situation would be substandard and hence would need to be modified, e.g. in terms of possible window area. However, for the current purpose of noise exposure estimations, the solution is considered to be satisfactory. Furthermore, it should be noted that for cases with the point buildings in the centre of block, only large flats were used, and in Series 5 only small flats were used for the towers.

For each apartment, the noise levels calculated at all facade elements constituted the possible input to the noise exposure calculations (using a maximum horizontal spacing of 5 m). The number of inhabitants in each apartment is in proportion to its floor area such that there are 2 persons per 100 m^2 (GFA).

The exposure value was given either as the highest level for each apartment or by using a bonus model where also the lowest level for the apartment was used as input. These calculations were made for both the small flat and the large flat layouts, even though the small flats were expected to mainly be insensitive to a bonus modelling. The bonus model used here reduces the exposure value by one third of the difference between the highest level (L_{most}) and the lowest level (L_{least}) for each apartment. This is based on Qside project results where a model of annoyance score is derived [16]. According to the full model in [16] the annoyance score is proportional to $aL_{most} + bL_{least}$, where a = 0.069 and b = 0.035. (Hence, since 0.069/0.035 ≈ 2, one can see the annoyance as approximately consisting of two parts L_{most} to one part L_{least}.) In reformulating this into a bonus model, it can be written as

$$s = L_{most} - (L_{most} - L_{least})/c,$$

where s is proportional to the annoyance score and $c = a/b + 1$ = 0.069/0.035 + 1 ≈ 3. Here, the bonus can be identified as the term $(L_{most} - L_{least})/c \approx (L_{most} - L_{least})/3$.

The results for sleep disturbance are less conclusive [34] and in the present work the same bonus model is assumed for both annoyance and sleep disturbance.

The grid noise map results (using a grid spacing of 1 m) was sorted in 5-dB-categories, including also a separation into yard areas and sidewalk areas, for further analysis. (See Results below.)

2.4. Prediction of DALY (Disability-Adjusted Life Year) due to the noise exposure

To compare the noise exposures between the cases of the present parameter study, quantitative comparison is made using the single-number DALY measure based on [13,14].

The DALY estimation has L_{den} and L_{night} facade values as input to predict the percentages of persons highly annoyed (HA) and highly sleep disturbed (HSD) using exposure–response functions (ERFs) for road traffic noise as in Eq. (1) [14,35].

$$HA = 78.9270 - a_{HA} \cdot L_{den} + b_{HA} \cdot L_{den}^2 \quad (1a)$$

$$HSD = 19.4312 - a_{HSD} \cdot L_{night} + b_{HSD} \cdot L_{night}^2 \quad (1b)$$

where
a_{HA} = 3.1162, b_{HA} = 0.0342
a_{HSD} = 0.9336, b_{HSD} = 0.0126.

The percentages of HA and HSD are converted into number of persons HA and HSD by estimating the number of persons inhabiting apartments at each facade exposure level, here in steps of 1 dB. The DALY contribution is estimated using disability weightings of 0.02 for number of persons HA and 0.07 for number of persons HSD [14]. The sum of the two DALY contributions (HA and HSD) gives the final DALY value as used here; other effects could be

Table 1
Road and building configuration data for all cases.

Seris no.	Description of series	case ID	Identical to case ID	Typology	Footprint	Floors	Street length	Traffic flow local roads	Gross Floor Area	Floor Space Index	Population	Ground Space Index	Network density	Open Space Ratio
					F (m^2)	L (-)	S (m)	ADT (vehicles/24 h)	GFA (m^2)	FSI (-)	P (-)	GSI (-)	N (m^-1)	OSR (-)
1	FSI constant	1.1		Closed yard (CY)	73,482	5.0	3591	1500	3,67,410	1.82	7,348	0.36	0.018	0.35
	FSI=1.82	1.2		U-shaped block (UB)	65,532	6.0	3591	1500	3,93,192	1.95	7,864	0.33	0.018	0.35
		1.3		Open corners (OC)	57,634	6.0	3591	1500	3,45,804	1.72	6,916	0.29	0.018	0.42
		1.4		I-shaped block (IB)	57,510	6.0	3591	1500	3,45,060	1.71	6,901	0.29	0.018	0.42
		1.5		L-shaped block (LB)	40,158	9.0	3591	1500	3,61,422	1.79	7,228	0.20	0.018	0.45
		1.6		Point building in yard centre (PC)	26,250	14.0	3591	1500	3,67,500	1.82	7,350	0.13	0.018	0.48
		1.7		Point buildings along road (PR)	31,500	12.0	3591	1500	3,78,000	1.88	7,560	0.16	0.018	0.45
2	Floors constant	2.1	1.1	Closed yard (CY)	73,482	5.0	3591	1500	3,67,410	1.82	7,348	0.36	0.018	0.35
	L = 5	2.2		U-shaped block (UB)	65,532	5.0	3591	1500	3,27,660	1.63	6,553	0.33	0.018	0.42
		2.3		Open corners (OC)	57,634	5.0	3591	1500	2,88,170	1.43	5,763	0.29	0.018	0.50
		2.4		I-shaped block (IB)	57,510	5.0	3591	1500	2,87,550	1.43	5,751	0.29	0.018	0.50
		2.5		L-shaped block (LB)	40,158	5.0	3591	1500	2,00,790	1.00	4,016	0.20	0.018	0.80
		2.6		Point building in yard centre (PC)	26,250	5.0	3591	1500	1,31,250	0.65	2,625	0.13	0.018	1.34
		2.7		Point buildings along road (PR)	31,500	5.0	3591	1500	1,57,500	0.78	3,150	0.16	0.018	1.08
2 Tr	Traffic flow varies with FSI	2.1	1.1	Closed yard (CY)	73,482	5.0	3591	1500	3,67,410	1.82	7,348	0.36	0.018	0.35
	L = 5	2.2		U-shaped block (UB)	65,532	5.0	3591	1340	3,27,660	1.63	6,553	0.33	0.018	0.42
		2.3		Open corners (OC)	57,634	5.0	3591	1178	2,88,170	1.43	5,763	0.29	0.018	0.50
		2.4		I-shaped block (IB)	57,510	5.0	3591	1176	2,87,550	1.43	5,751	0.29	0.018	0.50
		2.5		L-shaped block (LB)	40,158	5.0	3591	821	2,00,790	1.00	4,016	0.20	0.018	0.80
		2.6		Point building in yard centre (PC)	26,250	5.0	3591	537	1,31,250	0.65	2,625	0.13	0.018	1.34
		2.7		Point buildings along road (PR)	31,500	5.0	3591	638	1,57,500	0.78	3,150	0.16	0.018	1.08
3	FSI constant	3.1	1.1	Block size S	73,482	5.0	3591	1500	3,67,410	1.82	7,348	0.36	0.018	0.35
	FSI=1.82	3.2		Block size M	59,635	6.0	2688	2250	3,57,810	1.78	7,156	0.30	0.013	0.40
		3.3		Block size L	52533	7.0	2236	3000	3,67,731	1.82	7,355	0.26	0.011	0.41
		3.4		Block size XL	34729	11.0	1339	9000	3,82,019	1.90	7,640	0.17	0.007	0.44
	Floors constant	4.1	1.1	Block size S	73,482	5.0	3591	1500	3,67,410	1.82	7,348	0.36	0.018	0.35
	L = 5	4.2		Block size M	61,874	5.0	2688	2250	3,09,370	1.54	6,187	0.31	0.013	0.45
		4.3		Block size L	54645	5.0	2236	3000	2,73,225	1.36	5,465	0.27	0.011	0.54
		4.4		Block size XL	36090	5.0	1339	9000	1,80,450	0.90	3,609	0.18	0.007	0.92
5	Blocks with towers	5.1		Towers 8 floors	74,982	5.0	3591	1500	3,97,410	1.97	7,948	0.37	0.018	0.32
		5.2		Towers 12 floors	74,982	6.0	3592	1500	4,94,892	2.46	9,898	0.37	0.018	0.26
		5.3		Towers 16 floors	74,982	6.0	3593	1500	5,24,892	2.60	10,498	0.37	0.018	0.24
		5.4		Towers 32 floors	74,982	8.0	3594	1500	7,79,856	3.87	15,597	0.37	0.018	0.16
		5.5		Towers 32 floors	74,982	5.0	3595	1500	5,77,410	2.87	11,548	0.37	0.018	0.22
6	Floors constant	6.1	1.1	Street width 20 m	73,482	5.0	3591	1500	3,67,410	1.82	7,348	0.36	0.018	0.35
	L = 5	6.2		Street width 40 m	70,500	5.0	3591	1500	3,52,500	1.75	7,050	0.35	0.018	0.37
		6.3		Street width 80 m	64,456	5.0	3593	1500	3,22,280	1.60	6,446	0.32	0.018	0.43
7	Road vehicles limited	7.1		Street width 20 m	73,482	5.0	3591	9000	3,67,410	1.82	7,348	0.36	0.018	0.35
	to main street	7.2		Street width 40 m	70,500	5.0	3591	9000	3,52,500	1.75	7,050	0.35	0.018	0.37
	(based on series 6)	7.3		Street width 80 m	64,456	5.0	3593	9000	3,22,280	1.60	6,446	0.32	0.018	0.43
8	Closed yard with	8.1	1.1	Closed yard (CY)	73,482	5.0	3591	1500	3,67,410	1.82	7,348	0.36	0.018	0.35
	increasing building height	8.2		Closed yard (CY)	73,482	8.0	3591	1500	5,87,856	2.92	11,757	0.36	0.018	0.22
	(based on case 11)	8.3		Closed yard (CY)	73,482	12.0	3591	1500	8,81,784	4.38	17,636	0.36	0.018	0.15

Table 2
Used values for green roof insertion loss and facade absorption.

Frequency (Hz)	Green roof insertion loss (dB)	Absorption coefficient of vegetated facade (-)
25	-0.4	0.21
32	-0.6	0.21
40	-0.5	0.21
50	-0.4	0.21
63	-0.2	0.21
80	0.4	0.21
100	0.5	0.22
125	0.7	0.3
160	1.2	0.42
200	2.1	0.55
250	2.9	0.7
315	4.3	0.85
400	5.5	0.85
500	7.7	0.85
630	10	0.85
800	10.4	0.85
1000	10.9	0.85
1250	12	0.85
1600	12	0.85
2000	12	0.85
2500	12	0.85
3150	12	0.85
4000	12	0.85
5000	12	0.85
6300	12	0.85
8000	12	0.85
10000	12	0.85

included, e.g. cardiovascular disease and cognitive impairment [14], whereas annoyance and sleep disturbance are expected to dominate the impact on health and wellbeing [13]. The DALY measure as described above models the yearly disease burden in total for the inhabitants of the area. In the results shown below, we use a per person normalised DALY and display the results as DALY per 10 000 persons or as relative to a chosen reference case, Case 1.1 with small flats. (The number of inhabitants for each case can be used to calculate the corresponding total, non-normalised, disease burden.)

The main difference to previous uses of the DALY measure is here that the exposure values (L_{den} and L_{night}) are evaluated for different apartment layouts, also including a possible bonus on the exposure values if an apartment has a less noisy facade element, as described above. In addition, normally DALY estimates are applied to larger areas, e.g. whole cities or larger.

The ERF for annoyance (Eq. (1a)) originates from fitting a second-degree polynomial to data and displays a minimum in the response of 7.9 % at an exposure of L_{den} = 45.6 dB. Instead of allowing a larger response at lower exposures, the response for L_{den} = 45 dB and below is here limited to 7.9 %. This alteration makes the ERF monotonically increasing, thus preventing a possible prediction of false positive effects from increasing the noise level. Similarly is here made also for the ERF for sleep disturbance, limiting the response to 2.1 % for exposures of L_{night} = 37 dB and below. The resulting ERFs are displayed in Fig. 4.

It should also be noted that these ERFs are stated to have an exposure of 40 dB as a lower limit of application [14,35]. However, the responses are here assumed to follow the curves also at lower levels (as in Fig. 4). This approach is chosen in order to have continuity in outcome, and here makes a difference only for a few points of low L_{night} exposure values.

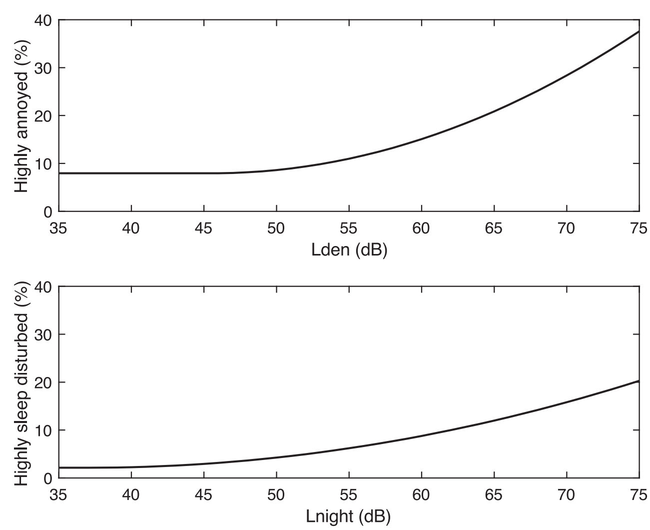

Fig. 4. Used exposure response functions (ERFs).

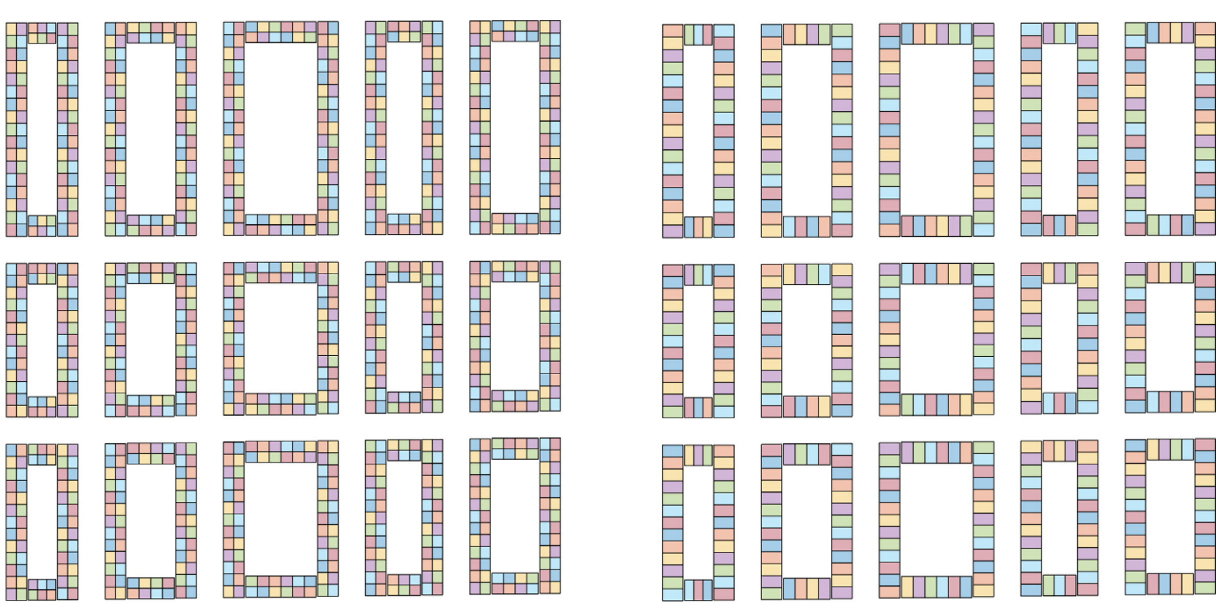

Fig. 3. Examples of apartment layouts for small flats (left) and large flats (right) for building type CY.

3. Results

The resulting facade noise exposures are displayed as histograms of noise exposure levels ($L_{Aeq,24h}$), as exemplified in Fig. 5 for the reference case: Case 1.1, closed inner yard (CY) and five floors. The *y*-axis shows the percentage of persons exposed. A second *y*-axis shows the corresponding DALY count per 10 000 persons inhabiting the area. Results for small flats (left) and large flats (right) as well as for no bonus (top) and including bonus for having also a less noisy facade element (bottom) are shown in Fig. 5. The sum of the DALY count is written in each plot.

In Fig. 5, for the small flats (left) it can be seen that when including the effect of the bonus model (left-top compared with left-bottom) the change of the histogram is small as well as the resulting DALY count difference: an improvement by ca 0.2 DALY per 10 000 from a value of 54.8 DALY per 10 000, i.e. a change of less than 1 %. On the other hand, for the large flats (right), the bonus model predicts a large improvement in DALY per 10 000: from 72.7 to 53.7, i.e. an improvement by more than 25 %. Looking at the change in the histogram (right-top compared with right-bottom), it can be seen that the modelled exposure when including the bonus of having access to also a less noisy facade element causes a shift of a large part of the noise exposure counts above 55 dB to end up below 55 dB.

The resulting DALY estimates for all cases of the parameter study are plotted in Fig. 6 in terms of improvement in percent relative to the reference situation Case 1.1 with small flats and no bonus. (The results corresponding to Fig. 6 are appended in Table A1.)

As can be seen from the results in Fig. 6, without bonus, the assumption of small flats results in a better overall performance than assuming large flats. However, with bonus included, the over-

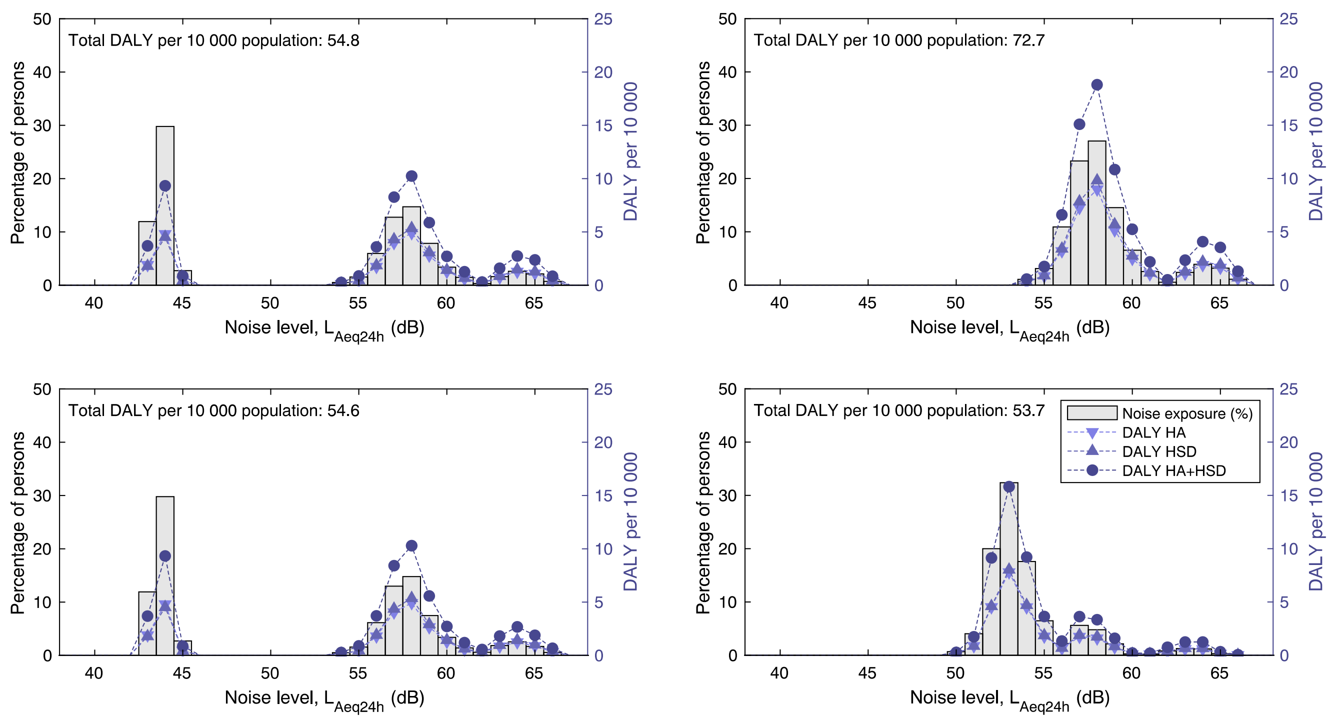

Fig. 5. Results for Case 1.1 displayed as histograms of noise exposures and DALY count: small flats (left), large flats (right), no bonus (top) and including bonus (bottom). DALY per 10 000 inhabitants is plotted for highly annoyed (HA), highly sleep disturbed (HSD) and in total (HA + HSD).

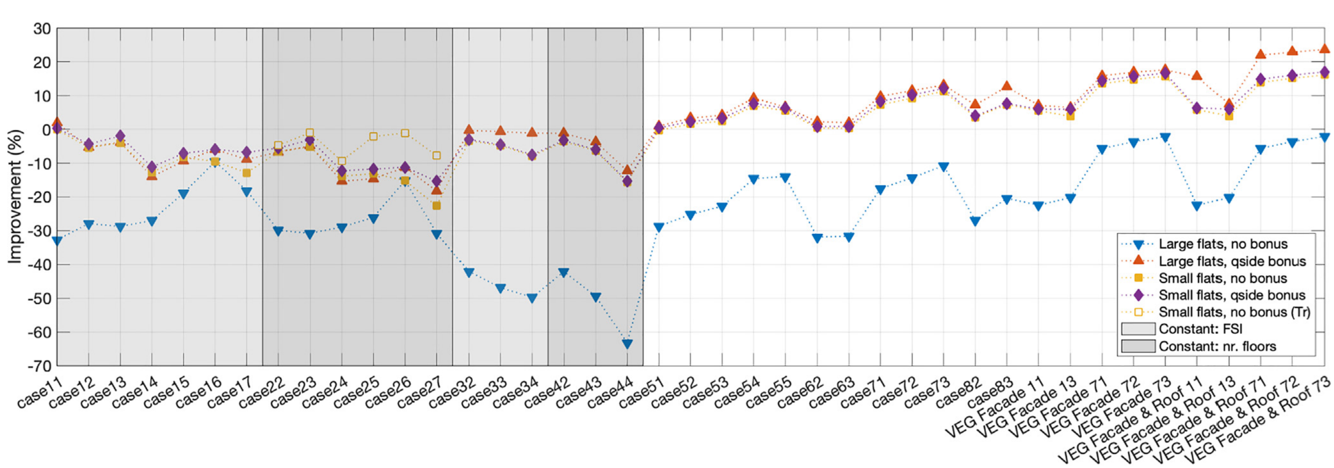

Fig. 6. Improvement (%) in DALY per inhabitant for all cases relative to the reference case (Case 1.1, small flats, no bonus). The dashed curve displays results for traffic flow varied with population, labelled (Tr) in the legend.

all performance for large flats is similar or better than that of small flats. The results for small flats in Series 1 (constant FSI) show that the use of closed inner yards, slightly open yards and U-shaped buildings (building types CY, OC and UB in Fig. 1) perform better than I-shaped, L-shaped and point buildings (building types IB, LB, PC and PR in Fig. 1). For Series 2 (where FSI varies) the above described trend holds when the traffic flow is kept constant. When the traffic flow is varied with FSI, the performance for the building types CY, OC and UB shows only moderate change and the result still holds that these building types perform better than I-shaped buildings. However, they are preferable to L-shaped and point buildings in centre of block only when the traffic flows are not changed with FSI.

For small flats, when the block sizes increase for closed inner yards (Cases 3.2–3.4 and 4.2–4.4), the performance drops. For large flats, the inclusion of bonus largely improves the performance for these cases. The addition of towers to perimeter blocks (Cases 5.1–5.5) is shown to enable improved performance.

When all local traffic is rerouted to a single road, i.e. the boulevardisation cases (Cases 7.1–7.3), overall improvement is shown for both small and large flats, both with and without bonus. When also increasing the width of that road (Cases 7.2 and 7.3), keeping the traffic flow constant, the predicted performance is improved further.

Concerning the predicted effects of vegetation surfaces, significant overall improvement is shown for facade vegetation whereas the additional effect of roof vegetation is insignificant when the block is opened in the corners: Case 1.3 shows negligible improvement when the vegetated roof is included. It should be noted that the insignificant effect of adding roof vegetation for small flats in the other cases (Case 1.1, and 7.1–7.3) is due to that the noise exposure is already very low in the yard, whereby the ERFs are constant or near-constant and hence insensitive to further noise reduction. However, when the bonus model is used for the large flats, the benefit of green roofs is accentuated.

The resulting area exposures are plotted in Fig. 7, in percentage values for 5-dB-classes of $L_{Aeq,24h}$, from < 50 dB to >65 dB. For the sidewalk areas it can be seen that when the building blocks are successively opened (Cases 1.1 through 1.6, and similarly for Series 2), the sidewalks become slightly less noisy. When the number of roads decreases and the traffic flows on the remaining roads increase, the proportion of noisy sidewalk areas increases, as in Cases 3.4 and 4.4. It can also be seen that when the traffic is moved to one road, less noisy sidewalk areas appear, as in Cases 7.1–7.3. Among these three cases, Case 7.1 has the largest proportion in the noisiest class (>65 dB) which is mainly due to that the sidewalks, with a constant width of 4 m, are modelled to be adjacent with the building facades and thus are moved further away from the driving lanes as the width of the street space increases in Cases 7.2–7.3. Furthermore, the effect of vegetating the facades is shown to provide an overall noise reduction at the sidewalk areas.

For the yard areas, it is shown that all cases with closed blocks provide noise levels below 50 dB, and when the building blocks are successively opened, the yards generally become more noisy, contrary to the corresponding trend for the sidewalk areas, as expected. The effect of vegetating the facades in Case 1.3 is shown to provide a large improvement where e.g. the proportion of yard area below 50 dB increases from 33 % to 61 %.

It is of interest to study the relations between the calculated DALY outcomes due to the road traffic noise and the morphological

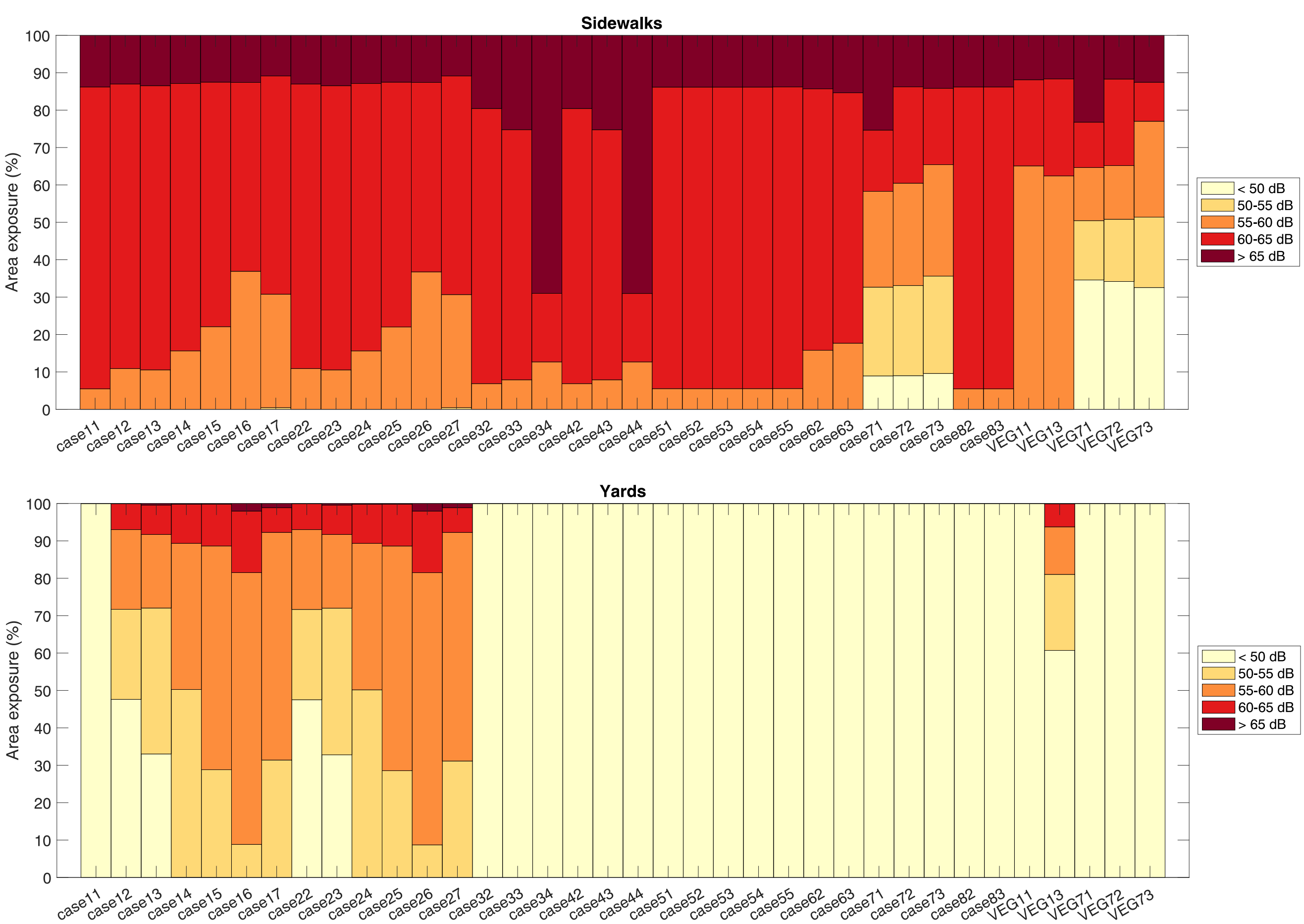

Fig. 7. Area exposures ($L_{Aeq,24h}$) for sidewalk areas (top) and yard areas (bottom). The cases denoted 'VEG' are for the vegetated facades.

parameters, wherein the effects of urban densification are of particular interest. For this, the calculated improvement in DALY relative to the reference case (Case 1.1) is plotted against FSI assuming constant traffic flow; FSI is proportional to number of inhabitants per unit area and thus links directly to the amount of densification. It can be argued that the assumption of unaltered traffic flow with FSI provides relevant results since for many urban densification projects the city government has the objective of non-increasing traffic flows, working with public transport and other counteracting measures. It should also be noted that Series 1 and 3 have constant FSI (by way of changing the number of floors) whereby the traffic flow is kept in proportion to the population. Letting the traffic flows vary with FSI is also of interest; however not further studied here. Fig. 8 shows the resulting scatter plot for small flats without bonus. As an overall trend of the cases studied here, it can be seen that larger improvements in DALY per person appear more frequently at increased FSI values. However, within these results, different trends can be identified. Among the different building types, with constant building height (i.e. Series 2, 5 floors), an increase in FSI improves the DALY performance (dashed trend line). On the other hand, keeping FSI constant among the different building types, by allowing a varying building height (Series 1), also shows a significant range in DALY improvement. Comparing the same building types from series 1 and 2 (i.e. Case 1.2 vs. Case 2.2, Case 1.3 vs. Case 2.3, etc.) shows that within the same building type, it is beneficial for DALY performance to increase FSI. The reason for the trend can be explained as a densification by adding additional top floors in less noisy places.

Among the cases that perform similarly or better than Case 1.1, Series 5 (i.e. adding towers) and Series 8 (i.e. increasing the number of floors) follow the same above-described trend of increased performance with increasing FSI. The reason can again be explained as a densification by adding new flats in less noisy places (e.g. using towers as in Series 5), possibly also lowering the noise exposure for existing flats (as in Series 8 where the closed blocks are given additional top floors, increasing the shielding of the yard).

It is also of interest to note that traffic concentration by increasing block sizes and thus reducing the number of streets (Series 3 and 4) is linked to decreased performance. However, similar to what was discussed for building types, densification of these larger blocks by adding floors, reduces this negative impact (compare Case 4.4 with 3.4 and Case 4.3 with Case 3.3). Traffic concentration without changes in block size (Series 7) is linked with an improved performance, as can be seen from comparing the results of Cases 7.1 and 1.1. The explanation is that even if the traffic concentration (i.e. boulevardisation) leads to an increase in noise level at some facade elements, the noise reduction at other places largely compensates in terms of DALY. Furthermore, concerning the boulevardisation cases (7.1–7.3), they display a trend of improved performance with decreasing FSI, which can be explained as being due to removing flats at noisy locations; when widening the road space, the flats closest to the traffic are removed and placed further away. (It can however be noted that Series 7 was chosen for studying the effects of boulevardisation and street space widening and a complementing series with constant FSI was not included here. For a real-case implementation, additional top floors for Cases 7.2 and 7.3 could compensate for the loss in FSI and be expected to not impair the performance.) The above-described trends in results are valid also for large flats with bonus with the exception of Series 3 which has less variation in performance with increasing block sizes (see Fig. 6).

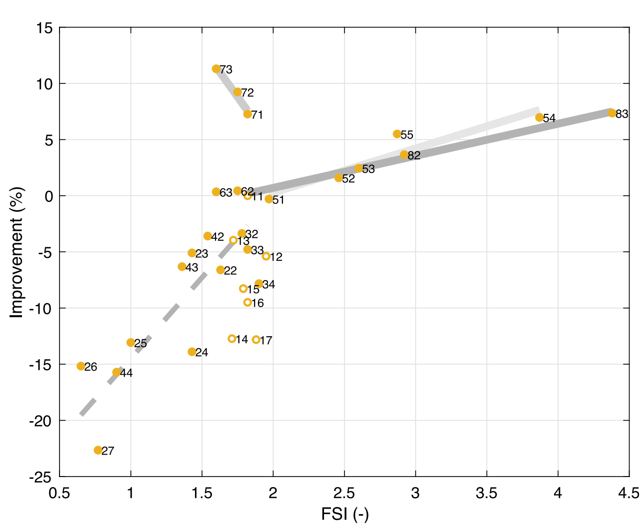

Fig. 8. Calculated improvement in DALY per person for small flats without bonus relative to the reference case (Case 1.1) plotted against FSI. The different cases are marked by numbers, e.g. '11' stands for 'Case 1.1'. Trend lines are drawn for Series 5 (light grey), Series 8 (dark grey), Series 7 (medium grey) and Series 2 (dashed grey line). Series 1 is shown as unfilled markers.

4. Discussion

Of the here studied facade noise levels and grid noise maps, the former has more established links with health and wellbeing, as also exploited here, whereas scientific results are scarce when it comes to describing links between the urban quality and the noise exposure in the surroundings to our dwellings, i.e. not limited to the facade exposure levels. Some indicative results exist (e.g. [36,37]), and future developments for good urban qualities could largely benefit from further research in this area.

The bonus model used here for estimating the improvement due to access to a less noisy facade, mainly effective for larger, floor-through, flats, is based on previous results where the facade noise levels were estimated using noise mapping software. Due to the tendency of existing noise mapping tools to underestimate the noise level in shielded areas, the current extension of using the indirect noise model for predicting the yard noise levels is expected to lead to an overall underestimation of the bonus, i.e. providing a conservative estimate of the improvement due to access to a less noisy facade.

This kind of bonus modelling has been suggested to not be used when the direct noise exposure is very high; it is stated in the *Soundscape Support to Health* project that the noise level should not exceed 60 dB ($L_{Aeq,24h}$, free field level) to avoid that more than 20 % experience annoyance or other adverse health effects [15]. However, in the present work, the bonus modelling is made without this limitation, motivated by the preference of having a continuous model, and also substantiated by more recent results [38].

Since the predicted bonus is in proportion to the noise level difference, according to the model used here, the bonus may become much larger (e.g. for some individual dwellings where the front-to-back noise level difference is large) compared to when using a bonus model in line with the *Soundscape Support to Health* project result, with a credit of 5 dB when the level at the less noisy facade is low enough, i.e. $L_{Aeq,24h} \leq 48$ dB, 2 m in front of the facade (see above). The discrepancy in bonus modelling indicates that further studies are needed to have a well-established bonus model. Furthermore, the indirect noise prediction model could benefit from further validation and development.

5. Conclusion

A parameter study has been carried out where noise exposure due to road traffic in an urban setting has been calculated and analysed for 31 cases of different morphologies. The effects of vegetation surfaces on facades and roofs were additionally studied for five cases.

Both smaller (single-sided) flats and larger (floor-through) flats were considered when evaluating the direct exposure from the roads and the indirect exposure at shielded or partly shielded inner yards. The combined use of a noise mapping software and the indirect noise model was shown to work as a possible calculation approach for predicting environmental noise exposures in urban areas including shielded and partly shielded inner yards.

The metric DALY (Disability-Adjusted Life Year), as an approximate quantification of the overall disease burden, has been used here in the evaluation of the parameter study results, using estimated annoyance and sleep disturbance from the calculated facade levels. Here, also the impact of a bonus model for additional facade elements of a flat having a lower noise exposure has been investigated. In the results for all cases, the single-sided flats showed better overall performance than the larger, floor-through flats when the bonus was not included. However, with the bonus, the floor-through flats gave a similar or better predicted overall performance compared with the single-sided flats. To distinguish between overall (average) performance and possible exposures at individual flats, histograms of noise exposure levels and DALY count were shown to be useful.

For the building types studied, with varying number of floors such that the population was kept constant (i.e., FSI constant), it was shown for smaller flats that the use of perimeter blocks with closed inner yards (CY), slightly open yards (OC) and U-shaped buildings (UB) perform better than the morphologies of I-shaped (IB), L-shaped (LB) and point buildings (PC and PR), except for the cases with very large yards, where the performance was shown to drop. When instead the number of floors is kept constant for the different building types, and if the traffic flow is allowed to vary with FSI, the performance for the building types CY, OC and UB shows moderate change and these building types still perform better than I-shaped buildings (IB); however they no longer outperform the L-shaped (LB) and centre point buildings (PC). Hence, I-shaped (IB) and point buildings along the road (PR) show the worst performance of the building types studied, both when the traffic flow increases with densification for a constant number of floors and when densification (and traffic flow) is kept constant by way of varying the number of floors.

For the larger flats, the inclusion of the bonus resulted in an improvement for all cases, particularly for larger block sizes with closed inner yards. It was also shown that perimeter blocks with fully enclosed yards perform better than building types with less enclosed yards, building density (FSI) being constant. Building types with slightly open yards (like OC studied here) may provide an attractive compromise solution due to its relatively good noise exposure situation at the same time as other than acoustics aspects, such as air pollution improvements, can be fulfilled by having non-closed blocks. In addition, when relying on the quiet side concept, the problematic corner flats, which do not have a facade element toward the inner yard (here circa one flat in ten for the closed yard cases, CY), are removed for the open corner cases (OC). Further, it was shown that densification with constant traffic flow improves performance for each studied building type from point buildings to perimeter blocks, which can be explained by the fact that additional top floors are added in less noisy, higher, places.

The results for adding towers to blocks with closed inner yards indicate that such morphology changes at least do not deteriorate the noise exposure, which could be of interest for air pollution improvements, for which the use of added towers may be suggested. Furthermore, boulevardisation, in the form of increasing the width of the main road and concentrating all local traffic there, was shown to improve the noise exposure situation. Also, traffic concentration in itself was shown to be beneficial in terms of total DALY count.

Results from using vegetation surfaces on facades and roofs showed significant overall improvement for facade vegetation and that closed inner yards benefit from vegetated roofs.

Grid map exposures at ground level have been calculated and analysed for sidewalk areas and yard areas, showing that when the building blocks are successively less enclosed (from CY to PC) the resulting levels are reduced on the sidewalks and increased in the yards. A benefit of facade vegetation has been shown also for the area exposures, e.g. largely improving the yard area for the buildings with open corners (OC).

In future work, a similar approach as used here by including the indirect noise exposure at inner yards could be applied to noise exposure estimates also for other noise sources than road traffic. And for road traffic, it is of interest to perform more large-scale studies where more variations of traffic flows and rerouting can be investigated. The use of a bonus model for access to less exposed dwelling facades could benefit from further studies and development. Also, the DALY metric seems useful to include in future work. Further studies of the project include the combined analysis of noise exposure and air pollution. For future studies and real-life implementation, the building types and results of the current work can be further developed and adapted to site-specific situations including retrofitting, e.g., in terms of mixed building types as well as design and positioning of building openings, mainly of interest for the buildings with open corners and for the U-shaped buildings.

CRediT authorship contribution statement

Jens Forssén: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Writing - original draft, Writing - review & editing, Visualization, Supervision, Funding acquisition. **Andreas Gustafson:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Writing - original draft, Writing - review & editing, Visualization, Supervision. **Meta Berghauser Pont:** Conceptualization, Methodology, Investigation, Resources, Writing - original draft, Writing - review & editing, Visualization, Supervision, Funding acquisition. **Marie Haeger-Eugensson:** Methodology, Investigation, Resources, Writing - original draft, Visualization, Supervision, Funding acquisition. **Christine Achberger:** Investigation, Visualization, Supervision. **Niklas Rosholm:** Validation, Investigation, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apacoust.2021.108436.

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