Using urban form to increase the capacity of cities to manage noise and air quality

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Abstract. *The top two environmental factors adversely affecting human health in Europe are air and noise pollution, with road traffic being the largest source. Urban density plays an important role in reducing car traffic. However, the benefits of reduced emissions per capita can still mean higher emissions locally, because of the number of people in the area. Therefore, this paper investigates how morphological parameters influence the local distribution of noise and air pollution. A parametric approach, based on the Spacematrix method, is used to study the impact of morphological parameters on the distribution of air and noise pollution, controlling for traffic mode, flows and speed. To compare the impact of exposure to noise and air pollution, their respective health burden is calculated using disability-adjusted life years (DALYs). The results, based on 31 models of different forms, show that the degree of openness greatly affects performance with opposite effects for noise and air pollution. Building types with slightly open yards, like open corner blocks, may provide an attractive compromise solution due to their relatively good noise exposure situation at the same time as the dispersion of air pollutants improves. Adding sound absorbing vegetation is an effective measure to mitigate noise, especially for blocks with openings, limiting the propagation of sound into the yard. Further, densification is beneficial for health if the increase in density does not increase traffic volume in the same proportion. Densification by adding towers on a perimeter building block gives the best results for health as it combines a less noisy yard, thanks to the enclosure of the yard with towers, which enhances turbulent mixing of air within the street canyon.*

Keywords: urban morphology, densification, air pollution, noise pollution, human health

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According to the World Health Organization (WHO), the top two environmental factors affecting the disease burden in Europe are air and noise pollution (WHO, 2018, 2019). Numerous studies have shown that air pollution, especially particles (such as PM2.5, PM10), contributes to long-term morbidity and mortality from cardiovascular and respiratory diseases (Rajagopalan and Brook, 2012; Fridell *et al*., 2014). Noise pollution is also shown to cause serious negative health effects due to long-term exposure of high-level traffic noise in dwellings, including annoyance, sleep disturbance and ischaemic heart disease (Basner *et al*., 2013; Munzel *et al*., 2014). Studies of the comparative burden of disease demonstrate that air pollution is the primary environmental cause of disability adjusted life years lost (DALYs), while environmental noise is ranked second (Stansfeld, 2015). One DALY represents the loss of the equivalent of one year of full health. DALYs are thus the sum of the years of life lost due to premature mortality and the years lived with a disability. In terms of total external costs, the burden of noise equals that of air pollution (Vienneau *et al*., 2015).

In general, emissions of particulate matter in Europe have not decreased in recent years and, in Sweden in 2019, the target level for annual averages for PM10 was exceeded at most traffic stations where measurements are carried out (Swedish Environmental Protection Agency, 2020). Furthermore, noise exposure and its associated disease burden will probably increase up to a level where the disease burden is similar to that attributable to traffic accidents (Knol and Staatsen, 2005).

Road traffic is the largest contributor in cities to both noise and air pollution (such as NO_x and particulates), and health improvements can be divided into three groups. First, reductions at the source (such as reduced traffic or cleaner cars); secondly, mitigation measures to distribute noise and air pollution to where it causes less harm (using noise barriers for example) and, thirdly, reductions at the receiver (for example better windows). Many urban studies have focused on the first, reducing car traffic, where the publication by Newman and Kenworthy (1999) is the most frequently cited. Their study, and many that followed, showed a strong correlation between higher population density and lower energy consumption and lower emissions related to transport. The results of these studies have significantly influenced the debate on sustainable urban development, through advocacy of the compact city concept. However, due to the divergence between local and global effects, the benefits of reduced emissions globally can still mean higher emissions locally. Therefore, this paper investigates how morphological parameters influence the local distribution of noise and air pollution, thus focusing on the second group of health improvements.

Urban form affects the distribution of air pollutants on city (macro) and neighbourhood (micro) scale. On the city scale, urban form contributes to changes in wind, temperature and humidity (Kwak *et al*., 2015), which influences the distribution of air pollutants both horizontally and vertically (Zauli Sajani *et al*., 2018). Urban form on the micro scale, more specifically the form, placement and height of buildings in relation to roads, affects local variations in air pollution concentration (Tominaga and Stathopoulos, 2016; Oke *et al*., 2017). For instance, courtyards with an opening toward a busy street reduce air pollution concentrations due to the enhanced wind ventilation (Haeger-Eugensson *et al*., 2019). In similar ways, the shape, orientation and volume of the building and the layout of open spaces including the street canyon geometry, influence air pollution dispersion and thus human exposure to air pollutants (Fu *et al*., 2017; Yang *et al*., 2020).

While human exposure to air pollutants is reduced by, for instance, opening the courtyard to enhance wind ventilation, the noise transmission through such an opening degrades the sound environment because buildings do not block noise entering the otherwise quieter courtyard (Hornikx and Forssén, 2011). At the same time, urban densification projects rely to a large extent on the *quiet side* concept, that is allowing higher noise levels toward the noisy street as long as a quiet (or damped) side to each apartment is guaranteed (for example, Göteborgs Stad, 2016). Other studies on the impact of urban form on sound levels show that traffic noise distribution patterns are impacted by building coverage, building height and street width (Wang and Kang, 2011; Tong and Kang, 2021; Yildirim *et al*., 2021).

In most of these investigations, statistical methods are used to extract the role of the different variables in case studies. Although this gives valuable information, it is hard to separate the impact of each morphological variable (such as coverage, building height, density, street width) and to control for variables such as traffic intensity. Furthermore, systematically investigating theoretical urban forms, where one can push some characteristics to their extremes, requires another approach. This paper therefore applies a parametric approach, allowing modification of one variable at the time such as building height, built density (floor space index, FSI) and street width, controlling all other variables. The aim is thus not to explain which variable is the most important for the distribution of noise and air pollutants in real cases, but to investigate whether, and to what extent, critical morphological parameters affect these distributions. The paper focuses on the distribution of pollutants caused by road traffic but includes pollutants on the macro scale as background concentrations. These background concentrations do not vary while the local distributions change as a result of the changes in form. Fu *et al*. (2017) have shown that an approach where a real case street network is combined with a parametric approach is effective because it allows inclusion of the distributions of real pollutants on the macro scale (the background concentrations) and a theoretical characterization of the impacts of morphological parameters on the micro scale (urban fabric, blocks and buildings), controlling for traffic mode, flows and speed.

To compare the impact of exposure to noise and air pollution, the health effects of both are calculated by estimating the health burden using DALYs. In what follows, first, the methodology of the study is described including the introduction of 31 urban models. Secondly, the findings are presented and, thirdly, the conclusions are presented and directions for future research are discussed.

Method

The Spacematrix method, as described in Berghauser Pont and Haupt (2007, 2010, 2021) is used to systematically test the impact of urban form on the distribution of noise and air pollution. Spacematrix is a method to describe urban forms parametrically and has earlier been used to investigate the impact of urban form on daylight performance (Berghauser Pont and Haupt, 2010) and noise pollution (Salomons and Berghauser Pont, 2012).

Spacematrix consists of a three-dimensional scatter graph that allows for a systematic comparison of urban fabrics of different forms. The coordinate system is set up as follows: the floor space index (FSI) is on the *y*-axis, ground space index (GSI) on the *x*-axis and network density (N) on the *z*-axis. Other 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 201535 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 defining the site are counted half). Furthermore, OSR can be derived from the variables FSI and GSI and is calculated as OSR = (1-GSI)/FSI (Berghauser Pont and Haupt, 2010, pp. 107–11).

By plotting a large number of observations (neighbourhoods) on the scatter graph, Berghauser Pont and Haupt showed convincingly that building types with similar morphologies, cluster, confirming earlier studies by Martin and March (Steadman, 2013). High-rise strip types and mid-rise block types with similar FSI, for instance, are found at distinct locations on the graph due to differences

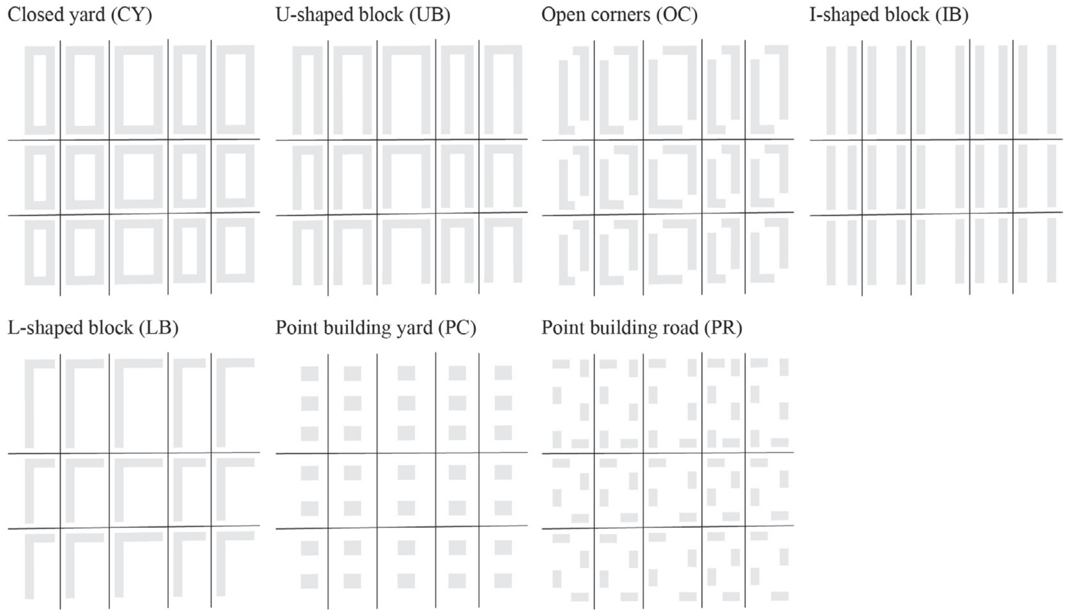

Figure 1. Vertical view of the model area for the seven distinct building types closed yards (CY), U-shaped blocks (UB), perimeter blocks with open corners (OC), slab buildings (I-shaped blocks, IB), L-shaped blocks (LB), point buildings that are positioned in the centre of the plot (PC) or along the road without setback (PR): buildings represented in grey and roads as black lines marking the road centre lines.

in GSI, OSR and L. Perimeter building blocks with a similar building height of 5 to 8 floors cluster in the right upper corner of the graph.

This clustering does not only allow description of well-known building types such as perimeter block buildings and point buildings quantitatively, but also allows examination of the role of the separate variables on, for instance, daylight performance; or, as in this paper, on exposure to noise and air pollution. The earlier study on daylight performance found that the daylight performance gradients are comparable to the OSR gradients, dropping mainly when both FSI and GSI increase (Berghauser Pont and Haupt, 2010).

To test the association between the Spacematrix variables and noise and air pollution, 31 different morphologies are used including seven distinct building types (Figure 1): 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). The GSI values decrease in order of building types CY, UB, OC, IB, LB, PR and PC which results in forms with less-enclosed yards. If building height is kept constant (for instance 5 floors), FSI values decrease when GSI decreases. Thus the model with closed yards (CY) has the highest FSI of the series of building types, L being constant. On the other hand, if FSI is kept constant for all building types, the buildings with a lower GSI must have more storeys. The model with point buildings (PC), for instance, must be 14 floors high to have the same FSI as the model with closed yards (CY) with a height of 5 floors. The combination of these variables does not only result in specific forms, but it also affects the feasibility of projects and the qualities of these environments in terms of, for instance, urban activity and diversity. Various studies have shown that higher-density neighbourhoods have better accessibility to public and commercial services, people use services more frequently, and the services provided are more diverse (Berghauser Pont *et al*., 2021).

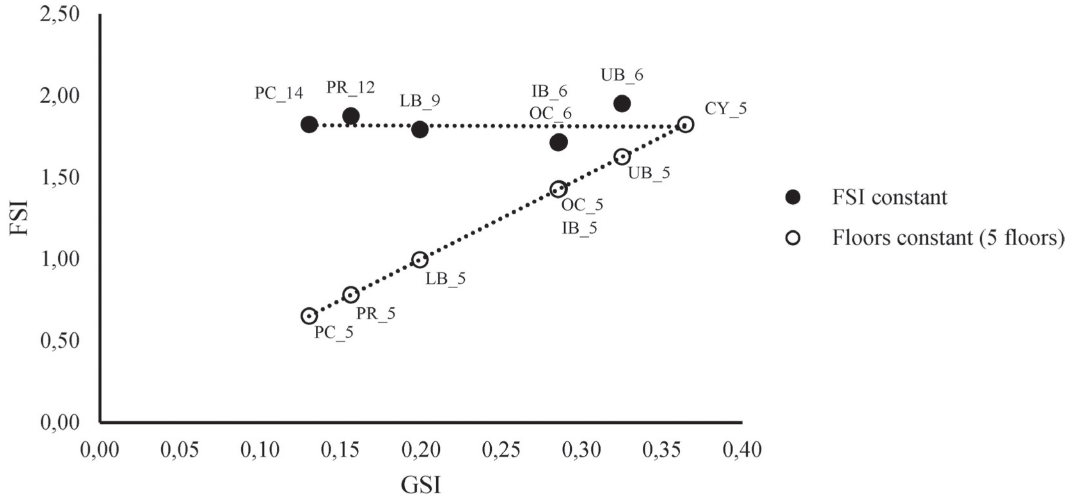

Figure 2. Spacematrix graph with the seven distinct building types PC, PR, LB, UB, OC, IB, CY. Series 1 investigates the types when FSI is constant and the number of floors (L) varies, while series 2 investigates the same types when the number of floors (L) is constant and FSI varies.

On the other hand, a higher OSR is beneficial for the daylight qualities in the yards and public spaces as well as inside the buildings (Berghauser Pont and Haupt, 2010). Higher OSR can be achieved with low FSI and GSI values, but also with high FSI if GSI is kept low, resulting in high-rise buildings in a spacious layout (such as models LB, PC and PR).

To investigate the role of the building types and the associated variable values systematically, the study freezes one variable at a time to test the impact of the others. For the seven distinct forms introduced above, one series is investigated when FSI is constant and L varies (Figure 2), while in the other series the number of floors (L) is constant and FSI varies.

The perimeter building type CY is chosen as the reference model and results are always presented in comparison with this reference model. The building types are positioned in a real urban setting (Figure 3) and have a fixed traffic volume of 1500 average daily traffic (ADT) in terms of vehicle movements in the new streets (of which 2.5 per cent are medium heavy and 2.5 per cent are heavy vehicles) driving at 50 km/h, while official data are used for the existing streets that surround the model area.

For the reference model, CY, we further investigate the impact of block size (and thus network density, N), street width (increased from the base value 20 m to 40 m and 80 m for one (the main) street and the addition of towers to perimeter buildings blocks (along the main street) (see Figure 4). When block size increases and the number of streets decreases, the traffic volumes are adjusted to keep the total traffic volume in the area constant. In addition, the models 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. These models are referred to as 'boulevardization', referring to two trends that often are implemented simultaneously: on the one hand, the redevelopment of arterial roads to multifunctional and multimodal streets (Stavroulaki and Berghauser Pont, 2020) and, on the other hand, the closing of streets for vehicular traffic, concentrating the remaining vehicular traffic on the boulevard. For instance in the central districts in Barcelona, whose grid-shaped layout was designed in the late-nineteenth century by the engineer Ildefons Cerdà, one in three streets will be turned into a green street, giving priority to pedestrians

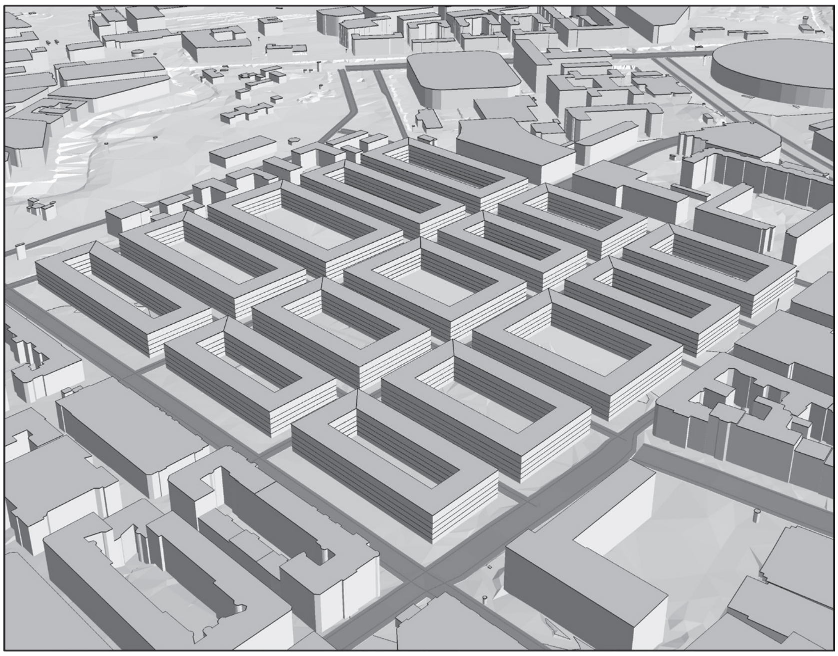

Figure 3. 3D view of the urban area where the reference models are located, exemplified for the reference model CY with perimeter building blocks of five floors (Case 1.1).

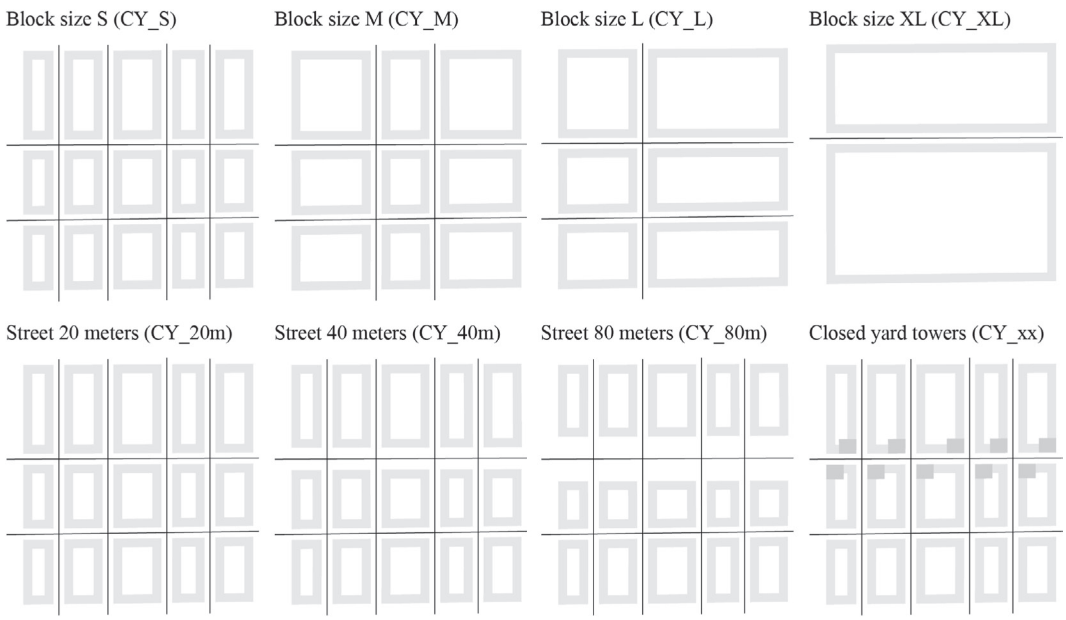

Figure 4. Vertical view of the model area based on reference model CY with variations in block size, street width of the main street (boulevard) and the addition of towers along the main street (boulevard): buildings represented in grey and roads as black lines marking the road centre lines.

and cyclists (Postaria, 2021). In the models used in this paper, the total traffic volume in the main street is increased to 9000 instead of 1500 ADT from the assumption that the same number of cars still must reach the dwellings and other functions in the neighbourhood.

The increase of density of the reference model (CY) is also investigated, increasing from 5 floors in the reference model to 8 and 12 floors, which entails a densification of 240 per cent (FSI increases from 1.82 to 4.38). Investigating the impact of densification on the exposure to air and noise pollution is important because higher densities are one of the main strategies to combat climate change (Gren *et al*., 2018) and this is one of UN Habitat's five principles for sustainable urban development (UN-Habitat, 2015). Finally, the role of vegetation on buildings (façades and roofs) on noise exposure is investigated for some of the building configurations.

The parameter values for all models are summarized in Table 1 and include 9 series. Series 1 and 2 investigate the impact of the different building types (PC, PR, LB, UB, OC, IB, CY) on the distribution of air and noise pollution (series 1 uses constant FSI, while series 2 uses constant building height, L); series 3 and 4 investigate the impact of block size (series 3 uses constant FSI, while series 4 uses constant L); series 5 studies the effect of adding towers of varying height to the reference model (closed perimeter building blocks of five floors, CY) as a means to densify an urban area (towers are 8, 12, 16 and 32 floors respectively); series 6 and 7 investigate the impact of street width (the main street is widened from 20 m to 40 and 80 m). In series 6 all traffic is still distributed evenly across the streets, while in series 7 all traffic is concentrated in the main street (boulevard); and series 8 investigates densification of the base type (CY) by increasing the number of floors from 5 to 8 and 12. Further, the role of vegetation on buildings (on both façades and roofs) on noise exposure are investigated for the base type CY, the building configurations with open corners (OC) as well as for the boulevardization models (series 9).

Prediction of exposure to noise and air pollution

The noise exposure is calculated using a combination of a commercially-available noise mapping software (SoundPLAN, version 8.0) and an extension (the Qside model) to better predict sound levels for enclosed inner courtyards (Estévez Mauriz *et al*., 2014). The Nord2000 model used within SoundPLAN is well suited to predict sound propagation from road vehicles to the nearest unshielded façade. The noise level is usually dominated by this direct exposure, but non-direct noise exposure that typically dominates shielded inner yards, where receiver positions do not have unobstructed paths from the sources, are not normally included to a sufficient extent in noise mapping. 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. This type of more complex indirect exposure is therefore calculated using the Qside model. The combined methodology (Nord2000 in SoundPLAN and Qside), implemented in Matlab, is described in Forssén *et al*. (2019).

The sound levels presented in this paper are values of the equivalent sound pressure level, LAeq, for a time period of 24 hours. It is a fundamental measurement parameter designed to represent a varying sound over a given time as a single number (Kragh *et al*., 2006). Using standard values for 24-hour road traffic distributions, conversions to the weighted long-term average day-evening-night noise level (L_{den}) and night noise levels (L_{night}) can be estimated, two mandatory indicators to be applied to strategic noise mapping according to the European directive on environmental noise (European Commission, 2002).

The effect of façade vegetation is modelled using a frequency dependent acoustic absorption assuming a 200 mm thick substrate covering 80 per cent of the façade surface above the ground floor, assuming a 20 per cent window area. The effect of vegetated roofs is modelled using a frequency dependent insertion loss (in dB) within the Qside level calculation. The insertion loss values are based on previous numerical modelling, extrapolated from calculation results for flat roofs (Hornikx *et al*., 2012).

The exposure to air pollution is calculated using the CFD-model MISKAM, a

Table 1. Road and building configuration data for all cases.

Description	Series	Case ID	Typology	Storeys L (-)	Traffic flow local roads ADT (vehicles/24h)	Floor Space Index FSI (-)	Block size w (m)	DALY noise change (%)	DALY air change (%)
Different building types, FSI constant	1	CY_5	Closed yard	5	1,500	1.82	111	ref	ref
		UB_6	U-shaped block	6	1,500	1.95	111	7%	-3%
		OC_6	Open corners	6	1,500	1.72	111	6%	-2%
		IB_6	I-shaped block	6	1,500	1.71	111	16%	-2%
		LB_9	L-shaped block	9	1,500	1.79	111	12%	-9%
		PC_14	Point building (centre yard)	14	1,500	1.82	111	8%	-19%
		PR_12	Point building (along road)	12	1,500	1.88	111	11%	-
Different building types, building height constant	2	CY_5	Closed yard	5	1,500	1.82	111	ref	ref
		UB_5	U-shaped block	5	1,500	1.63	111	9%	-1%
		OC_5	Open corners	5	1,500	1.43	111	7%	-2%
		IB_5	I-shaped block	5	1,500	1.43	111	18%	-2%
		LB_5	L-shaped block	5	1,500	1.00	111	17%	-8%
		PC_5	Point building (centre yard)	5	1,500	0.65	111	13%	-10%
		PR_5	Point building (along road)	5	1,500	0.78	111	21%	-
Same as series 2, *traffic flow varies with FSI	2*	CY_5*	Closed yard	5	1,500	1.82	111	ref	-
		UB_5*	U-shaped block	5	1,340	1.63	111	7%	-
		OC_5*	Open corners	5	1,178	1.43	111	3%	-
		IB_5*	I-shaped block	5	1,176	1.43	111	13%	-
		LB_5*	L-shaped block	5	821	1.00	111	5%	-
		PC_5*	Point building (centre yard)	5	537	0.65	111	-1%	-
		PR_5*	Point building (along road)	5	638	0.78	111	5%	-
Based on type CY, different block sizes, FSI constant	3	CY_S_5	Closed yard Block size S	5	1,500	1.82	111	ref	ref
		CY_M_6	Closed yard Block size M	6	2,250	1.78	154	2%	3%
		CY_L_7	Closed yard Block size L	7	3,000	1.82	182	3%	-19%
		CY_XL_11	Closed yard Block size XL	11	9,000	1.90	286	0%	-32%
		CY_B_80m	Closed yard Street 80 m	5	9,000	1.60	111	-12%	-

Table 1. (*Continued*)

Description	Series	Case ID	Typology	Storeys L (-)	Traffic flow local roads ADT (vehicles/24h)	Floor Space Index FSI (-)	Block size w (m)	DALY noise change (%)	DALY air change (%)
Based on type CY, different block sizes, building height constant	4	CY_S_5	Closed yard Block size S	5	1,500	1.82	111	ref	ref
		CY_M_5	Closed yard Block size M	5	2,250	1.54	154	3%	3%
		CY_L_5	Closed yard Block size L	5	3,000	1.36	182	6%	-25%
		CY_XL_5	Closed yard Block size XL	5	9,000	0.90	286	14%	-40%
Based on type CY, added towers along main street	5	CYT_8	Closed yard Towers 8 floors	5	1,500	1.97	111	1%	-20%
		CUT_12	Closed yard Towers 12 floors	6	1,500	2.46	111	-1%	-20%
		CYT_16	Closed yard Towers 16 floors	6	1,500	2.60	111	-2%	-27%
		CYT_32	Closed yard Towers 32 floors	8	1,500	3.87	111	-8%	-28%
Building type CY, different widths main street, building height constant	6	CY_20m	Closed yard Street 20 m	5	1,500	1.82	111	ref	ref
		CY_40m	Closed yard Street 40 m	5	1,500	1.75	111	0%	6%
		CY_80m	Closed yard Street 80 m	5	1,500	1.60	111	0%	-4%
Same as series 7, vehicles limited to main street (Boulevardisation)	7	CY_B_20m	Closed yard Street 20 m	5	9,000	1.82	111	-8%	36%
		CY_B_40m	Closed yard Street 40 m	5	9,000	1.75	111	-9%	-35%
		CY_B_80m	Closed yard Street 80 m	5	9,000	1.60	111	-11%	-43%
Based on type CY, different building heights	8	CY_5	Closed yard 5 storeys	5	1,500	1.82	111	ref	ref
		CY_8	Closed yard 8 storeys	8	1,500	2.92	111	-5%	-32%
		CY_12	Closed yard 12 storeys	12	1,500	4.38	111	-11%	-34%
Same as series 8, *traffic flow varies with FSI	8*	CY_5	Closed yard 5 storeys	5	1,500	1.82	111	ref	ref
		CY_8	Closed yard 8 storeys	8	1,500	2.92	111	-5%	-32%
		CY_12	Closed yard 12 storeys	12	1,500	4.38	111	-11%	-34%
Adding vegetation (roofs and façades)	9	CY_5	Closed yard	5	1,500	1.82	111	-14%	-
		OC_5	Open corners	5	1,500	1.43	111	-11%	-
		CY_B_20m	Closed yard Street 20 m	5	9,000	1.82	111	-13%	-
		CY_B_40m	Closed yard Street 40 m	5	9,000	1.75	111	-13%	-
		CY_B_80m	Closed yard Street 80 m	5	9,000	1.60	111	-12%	-

computational fluid dynamic model designed for air pollution dispersion calculations at microscale (Eichhorn and Bálczó, 2008). At this scale, buildings and other obstacles strongly modify the ground level air flow and thus dispersion conditions. Air pollution modelling in urban and built-up areas therefore requires a fine-scale three-dimensional model that can take into account the impact of buildings, to obtain realistic dispersion patterns (for example, Haeger-Eugensson *et al.*, 2019). A comparison between calculated NO_2 concentrations using CFD-model (used in this paper), commonly used Gauss models and and measured values of NO_2 concentrations is described in Haeger-Eugensson *et al.* (2019). Wind field and dispersion calculations for NO_X and PM_{10} with MISKAM were conducted for all 31 different forms (similar to that shown in Figure 3), creating individual wind field and dispersion patterns for each of the studied forms.

Calculating DALY for the health effects of air and noise pollution

A quantitative comparison using a single-number indicator is preferable to compare the exposures of noise and air pollution. For this purpose, the DALY metric is used (WHO 2011, 2018). In this paper, the results show a per person normalised DALY for the health effects of air and noise pollution and display the results as DALY per 10000 persons.

In general, DALYs can be calculated using the equation DALY = AB·D·S. The attributable burden (AB) is the number of people in a certain health state as a result of exposure to the environmental factor that is being analyzed, in this paper noise and air pollution. Duration (D) is set to one year for morbidity and for mortality. The severity (S) is a weight factor varying from 0 (healthy) to 1 (death), and is determined by experts including clinicians and researchers. In this paper, the input variable of this equation that varies is AB; more exactly, the noise and air pollution exposure. For noise exposure L_{den} and L_{night}, façade values are used as input to predict the percentages of persons highly annoyed (HA) and highly sleep disturbed (HSD) using exposure-response functions for road traffic noise (Brown and van Kamp, 2017). 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 façade exposure level in steps of 1 dB (for more details, see Forssén *et al.*, 2019).

Calculation of DALY for air pollution is based on the number of persons exposed to different levels of air pollution concentrations (here NO_X), an estimated effect from epidemiological studies (exposure-response functions, both for mortality and morbidity), a baseline rate for the health effect and the calculated NO_X-concentrations in the study area outdoors. A simplifying assumption was made that 50 per cent of people living in the urban area examined are exposed to pollution concentrations on the sidewalks where pollution is higher, whereas the other 50 per cent are exposed to lower concentrations in the yards. In this way a DALY-value for each specific building form has been calculated based on the spatial air pollution pattern. It is not the absolute number of DALY for each building form that matters in this study but the difference in DALY between the various typologies presented in Table 1.

Results

The DALY results are presented with the perimeter building type CY as the reference model, where a decrease from this reference model indicates an improvement from a human health perspective (DALY reduces), while an increase indicates the opposite (DALY increases). Results are presented for each of the exposures (noise and air pollution) separately. DALY for the reference model CY due to noise pollution is 54 per 10000 inhabitants, calculated for relatively large apartments with windows towards both the quieter yard and noisier street including a bonus for having access to a less-noisy side. For smaller one-sided apartments, DALY is slightly higher (55)

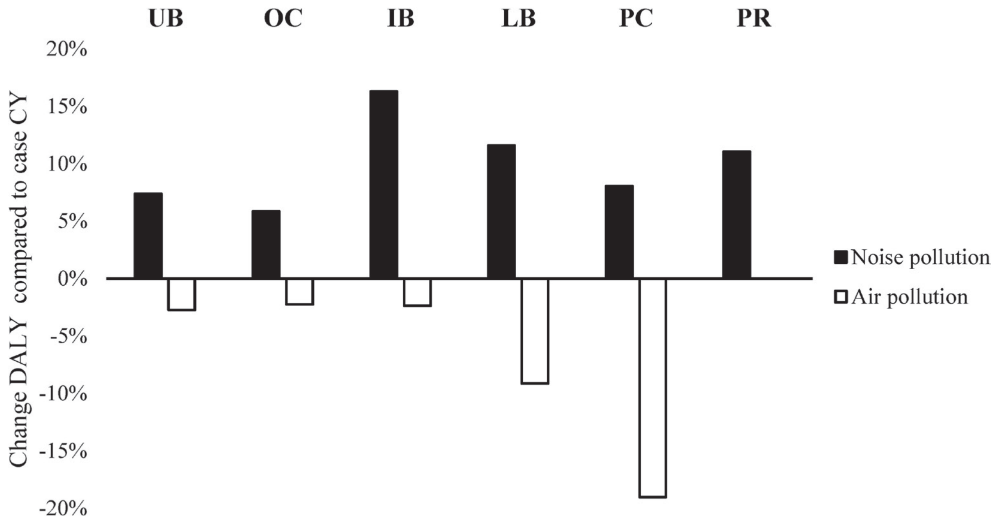

Figure 5. Changes in DALY for different forms compared to case CY. There was no air pollution data for model PR.

because half of the apartments do not have a quiet side at all and are exposed to more noise, while the other half are completely facing towards the quiet yard. This slightly affects the total outcome, because more people are exposed to too-high sound levels. Because the difference is small, we report only results for the large apartments (for all results, see Forssén *et al*., 2019).

The DALY for the reference model CY due to air pollution is 618 per 10000 inhabitants and thus a factor of 11 higher than DALY noise. The total DALY count for air pollution is so much higher because of its sensitivity to the background level determined by the surrounding city and region. For this study, we focus on the relative change in DALY, for both noise and air pollution, because we want to know how urban form on the micro and meso scale influences the distribution of pollutants.

The results are presented in following four themes. First, the impact of different block types on DALY performance is presented using all models from series 1 with constant FSI. Next, the role of densification for each of these types is presented comparing series 1 with 2. In this theme, series 5 is also considered, where towers are added to the reference model CY, as is series 8, where the number of floors of the reference model is increased from 5 to 8 and 12 floors respectively. The third theme concerns boulevardization and covers increasing block size, widening the main street and concentrating traffic flows on the main street. Finally, the role of vegetation is presented.

Impact of different block types

The results of the calculated DALY for each block type with a constant FSI (series 1) shows that the degree of openness has a considerable effect on performance with opposite effect for noise and air. In relation to noise pollution, there is an adverse effect on human health when opening the perimeter building block (CY); DALY increases in comparison to the reference model CY. The blocks with strip buildings (IB) are least favorable if the aim is to reduce noise exposure, followed by L-shaped buildings (LB) and point buildings (PC) (Figure 5). The opposite is the case for air pollution where exposure decreases in the more open forms (DALY decreases), notably the L-shaped buildings (LB) and point buildings (PC) perform better than the perimeter building block with closed or partly opened yards (CY, UB, OC).

The strip buildings (IB) are the worst combination with an increase in DALY of more than 15 per cent relating to noise and only

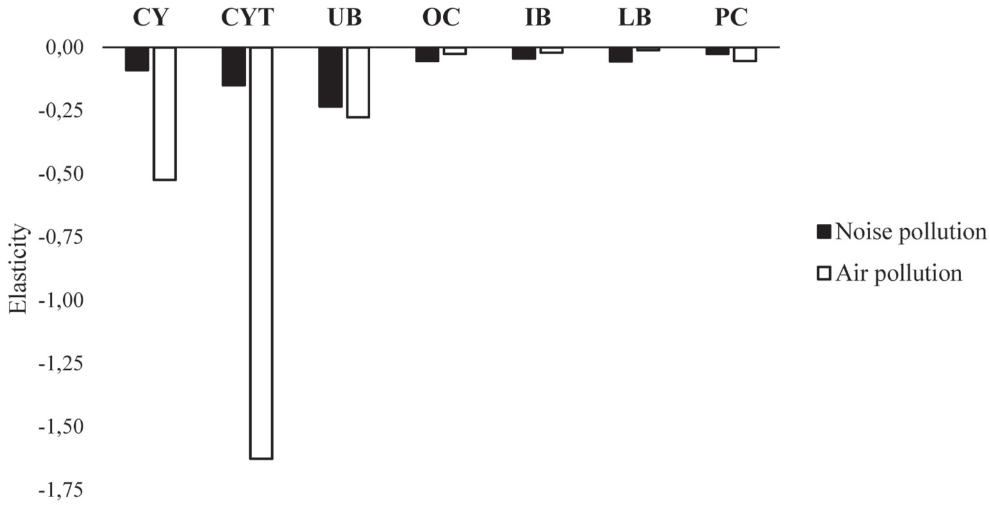

Figure 6. Elasticity of the different forms. The bars in the graph show how much DALY decreases when FSI increases by 1 per cent.

little improvement relating to air pollution. Block types with open corners (OC) and point buildings (PC) can provide an attractive compromise due to a relatively good noise exposure situation at the same time as air pollution improves. The overall disease burden (DALY) increases slightly in relation to noise exposure from 5 per cent for the open corner solution (OC) to 8 per cent for the point buildings (PC), while DALY linked to air pollution decreases with almost 20 per cent for point buildings (PC). It should be noted that these point buildings profit from being placed far away from the traffic. Placing the point buildings closer to the street (PR) worsens the exposure to air pollution and would probably also reduce the positive results in relation to air pollutants.

Impact of densification

Densification improves the performance for all different forms, meaning that DALY per 10000 inhabitants decreases as is shown in Figure 6 using the elasticity coefficient. Elasticity is an effective measure to present the sensitivity of one variable, here DALY, to a change in another variable, here FSI. For instance, if the FSI of the perimeter building blocks (CY) is increased by 10 per cent, DALY is estimated to decrease by 1.0 and 2.4 per cent for noise and air pollution respectively (Figure 5). In general, the more closed blocks have a higher elasticity and thus profit more from an increase in FSI than the L-shaped buildings (LB) and point buildings (PC). Densification by adding towers to the perimeter buildings (CYT in Figure 6) is shown to be very effective in reducing DALY. The elasticity coefficient in relation to air quality is far higher (reduction of 16 per cent) than all other elasticity coefficients. The reason is that buildings reaching above the general roof level (the added towers) can lead higher wind speed down to ground level. Thus, when adding towers to the closed yard form (CY), the increased ventilation from the higher buildings causes improved ground level dispersion, resulting in decreased DALY. Furthermore, densification takes place further away from the source which reduces exposure to both air pollution and noise. It should be noted that all densification scenarios were tested without varying traffic flows with the argument that traffic volumes decrease in denser environments due to an increased usage of other modes of traffic, such as active modes such as walking and public transport (Berghauser Pont *et al*., 2021). It cannot be expected, however, that traffic will not increase at all; and a test was therefore also conducted for noise where vehicle flows vary proportionally to FSI;

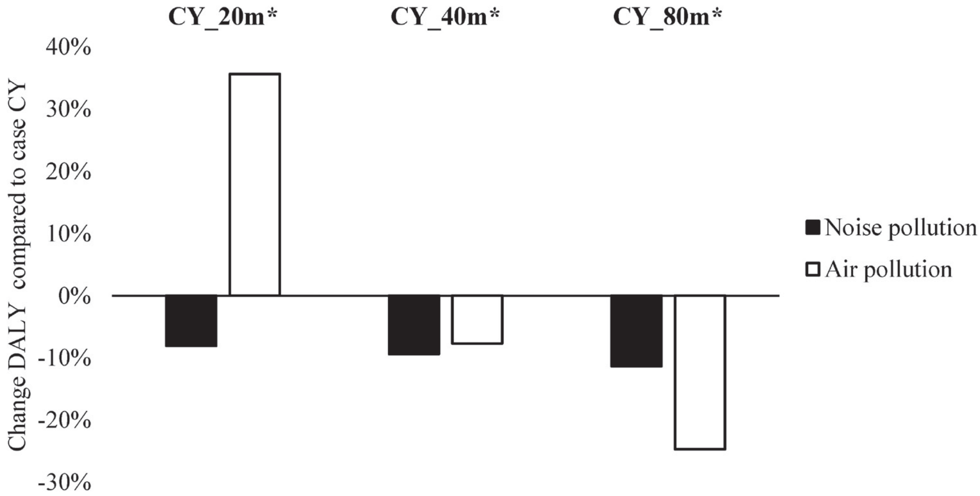

Figure 7. Changes in DALY when local traffic is rerouted to a single road compared to case CY. In the first case (CY_20m*), the street with all traffic has the same width as in case CY, while the other two cases have a wider street of 40 and 80 m respectively (CY_40m* and CY_80m*).

more traffic is assumed when FSI increases. The results of this test show that the positive effects described above are partly impaired. Therefore, we need to ensure that road traffic indeed is not increasing when density is increased, which we know from many studies can be expected because things in general are more accessible and thus walkable in dense environments.

Impact of boulevardization

When the block sizes for perimeter building blocks (CY) are increased from approximately 90 × 90 m to 130 × 130, 170 × 170 and 280 × 280 m, DALY for noise exposure increases, especially impairing model 4.4 which has the largest block size with the same number of floors as the reference model CY. However, as was discussed above, densification of these larger blocks by adding floors reduces this negative impact by reducing noise propagation into the closed yards. The trend in relation to air quality is the opposite because the longer streets without crossings reduce ground level dispersion, resulting in increased DALY.

Traffic concentration without changes in block size is linked with an improved overall performance except for impairment of air quality in the case of a relative narrow (20 m) street (Figure 7). When increasing the width of that street to 40 or 80 m (cases CY_40m and CY_80m respectively), performance is improved in relation to both air and noise pollution exposure, despite the concentration of traffic. The reason is that the receiver (buildings and pedestrians) are located further away from the source (vehicles) and, furthermore, the wider streets allows better ventilation.

Impact of vegetation

Concerning the predicted effects of sound-absorbing vegetation surfaces, significant overall improvement is shown for façade vegetation whereas the additional effect of sound-absorbing roof vegetation is good for the perimeter building blocks (CY) but insignificant when the block is opened in the corners (OC); the explanation being that the existence of façade openings (as for OC) causes a dominant noise contribution that makes the effect of vegetated roofs negligible (Figure 8). The combination of green façades and roofs with the boulevardization concept, where vehicle traffic is rerouted to the main street with a

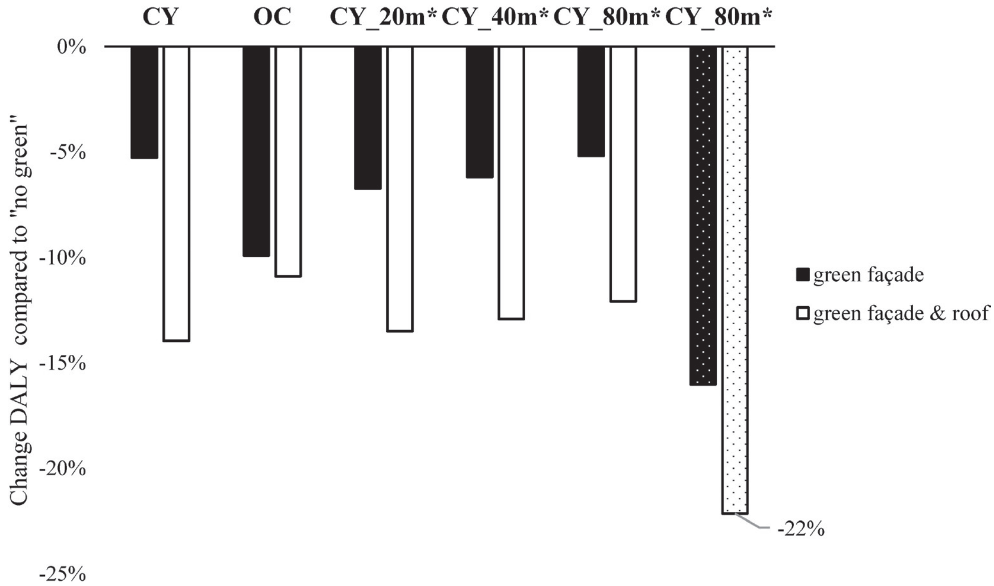

Figure 8. Changes in DALY in relation to noise pollution when sound-absorbing vegetation is added. The bars with solid fill show the comparison of the same case with or without vegetation, while the dotted bars show the comparison of case CY_80m* with vegetation with the reference model CY without vegetation.

width of 80 m (CY_80m), reduces DALY to 22 per cent (see the dotted bars in Figure 8).

Some types of vegetation also have a positive effect on the particle content and NO_2 by filtration, but it is important to choose the right type of vegetation. The positive effect of trees can, for example, disappear if the wind is slowed down by their placement in too-narrow streets. The blocking of the wind by trees can be avoided by planting bushes that are also effective in terms of filtration.

Discussion and conclusion

A parameter study has been carried out where exposure to noise and air pollution due to road traffic in an urban setting has been simulated and analysed for 31 models of different forms. The metric DALY, as an approximate quantification of the overall disease burden, has been used here in the evaluation of the parameter study results to be able to compare the effects in relation to both noise and air pollution. The total DALY count for air pollution is 11 times higher than the DALY count for noise pollution, which confirms the comparative burden of disease studies demonstrating that air pollution is the primary environmental cause of DALYs, while environmental noise is ranked second (Stansfeld, 2015).

For the building forms studied, it was demonstrated that the use of perimeter blocks with closed inner yards (CY), slightly open yards (OC) and U-shaped buildings (UB) perform better than the forms of I-shaped (IB), L-shaped (LB) and point buildings (PC and PR) when noise exposure is considered. The opposite is the case when the exposure to air pollution is considered, highlighting the need to consider both if improving health in general is the objective. What seems to be optimal for noise exposure, is not necessarily as positive when air pollution is considered. Building types with slightly open yards, such as the open corner blocks (OC) studied here, may provide an attractive compromise solution due to their relatively good noise exposure situation at the same time as they allow a slightly improved dispersal of air pollutants. The point buildings (PC) seem to behave similarly, but here it is merely the distance from the source (of pollution) than the form of the buildings that matters as was shown with the model with point buildings that are closer to the streets (PR). Opening the blocks in the corners has another advantage as corner flats are avoided, which do not have a façade toward the quiet inner yard and often have a less beneficial daylight performance. More research is needed to better understand what the size of openings and its design should be to increase air flow to 'blow the street clean', while at the same time reduce noise reaching into the courtyard. Green façades in the openings of the blocks have been shown to be an effective mitigation measure to do so.

Densification improves performance for all models (from point buildings to perimeter building blocks), which can be explained by the fact that additional top floors are added in higher and thus less exposed places. Adding towers to perimeter building blocks instead of raising the whole perimeter building has been shown to be effective, where a 10 per cent increase in density (through the added towers) results in a 16 per cent DALY reduction. This hybrid block type combines the positive effects on the dispersal of air pollution by adding towers without increasing noise exposure because the yard is still completely enclosed (and thus quiet). The more exposed apartments in the towers, which do not have a quiet side, have lower sound levels than those near the street because they simply are further away from the source of noise, resulting in an overall positive effect for human health. In addition to varying the building height and geometric variation, we know from previous research that it is advantageous, regarding both air and noise, to have such variations also on the scale of the façade, such as recessed sections, balconies, window niches and decorations. Furthermore, results related to vegetation in this study show significant overall improvements concerning noise exposure when using façade vegetation when blocks are opened, while perimeter building blocks benefit from green roofs.

Boulevardization, in the form of increasing the width of the main road and concentrating all local traffic there, reduces the exposure to noise and air pollution. This main street should be wider than 20 m to avoid negative effects of the concentrated traffic situation. With a 40 m street width and concentrated traffic, the DALY related to both noise and air pollution decreases by almost 10 per cent. The exact street width should be investigated further and depends on the combination of traffic flow, building type and building height. When developing tree planting strategies for the main road, the blocking of wind should be considered carefully to avoid losing the positive influence on air pollution of widening the street (Karttunen *et al*., 2020).

To summarize these conclusions, the effectiveness of mitigation measures to reduce negative health effects related to noise and air pollution are depicted using a scale between green for a positive contribution of the measure and red for a negative contribution (Table 2). The mitigation measures that do well both in terms of reducing noise and air pollution are particularly interesting from a planning perspective. The same results are also depicted as design strategies in an abstracted real case in Gothenburg, Dag Hammarskjöldsleden, where the city proposes densification along a new urban boulevard (Göteborgs Stad, 2021) (Figure 8).

In future work, the role of street configuration can be added in the urban models to predict the distribution of traffic flows instead of assigning them based on density as we did in this study. One street is then not assigned to be the main street, but through analysis, the main street is the results of the analysis of the street network, for instance using Space Syntax.

Furthermore, this would allow for the inclusion of the volumes of pedestrian flows and could give insight about how the exposure to noise and air pollution affects people moving through the city. Instead of intensities of people in buildings that are exposed, the focus would then shift to intensities of people walking the streets that are exposed. The exposure to pollutants in public space is less studied because there is no regulation in place, but we know that noise disturbance for instance in parks can have negative impact on well-being (Skärbäck *et al*., 2014).

Table 2. Effectiveness of the mitigation measures to reduce negative health effects related to noise and air pollution.

	Contribution to reduce negative health impact (DALY) related to:			
	noise pollution		air pollution	
Mitigating measure	**negative**	**positive**	**negative**	**positive**
Perimeter building blocks with enclosed courtyards				
Blocks with strip buildings, L-shaped buildings or point buildings				
Perimeter building blocks with small openings (open corners, U-shaped buildings)				
Adding green façades in openings of perimeter building blocks (noise absorbing)				
Adding green roofs on perimeter building blocks (noise absorbing)				
Densification of perimeter building blocks by adding towers without increased traffic				
Densification of perimeter building blocks by adding towers (traffic increases proportional to FSI)				
Densification of perimeter building blocks by adding floors without increased traffic				
Densification of perimeter building blocks by adding floors (traffic increases proportional to FSI)				
Larger blocks (and thus fewer streets with more traffic)				
Concentration of traffic on the main street (without widening the street)				
Concentration of traffic and widening of the main street (boulevardization)				

Finally, the DALY metric has shown to be useful for including different environmental factors in health impact studies, here air pollution and noise. In future work, additional factors related to the urban environment can be studied, for instance heat island effects. The addition of urban heat islands is important, since heatwaves are becoming more extreme and frequent with significant negative impacts on the health and comfort of urban populations (Perkins-Kirkpatrick and Lewis, 2020).

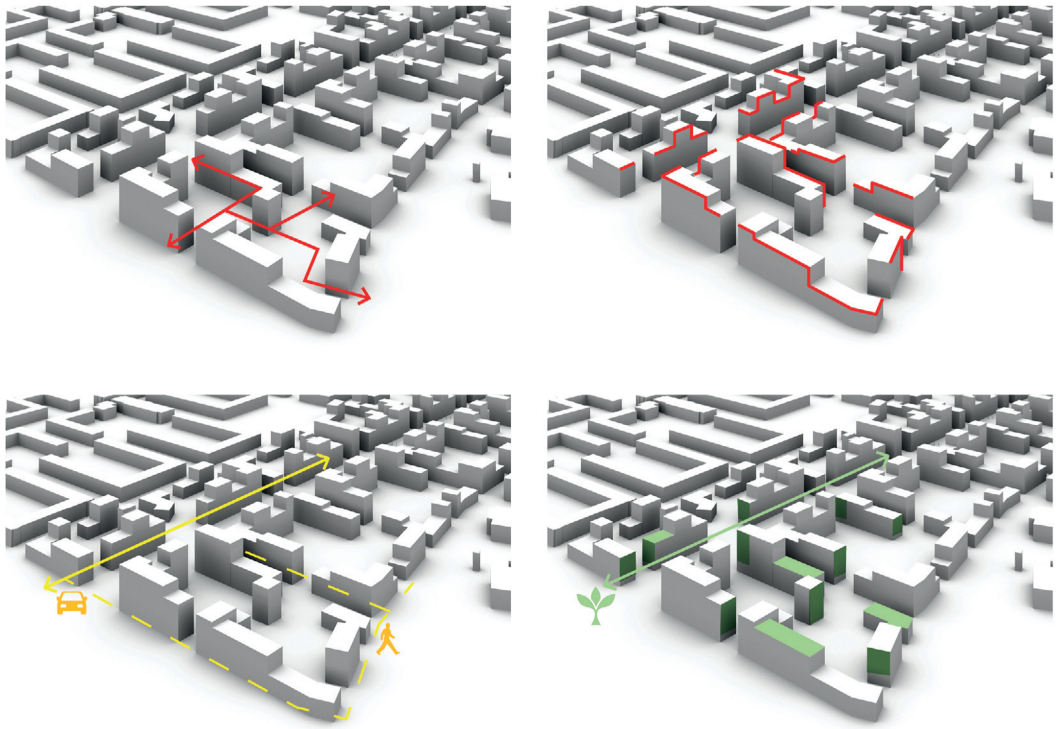

Figure 9. Design guidelines based on the findings (Forssén *et al.*, 2021): opening blocks to improve air quality (top left); varying building height to increase density and improve air quality and reduce noise exposure (top right); concentrate car traffic in the main road; plant trees in the wider street (bottom left) and add green façades as well as green roofs (bottom right).

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