Thesis for the Degree of Licentiate of Engineering

The urban space and the sound environment

Tools and approaches

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‘Good space is used space.’

Bill Hillier

Abstract

Cities are always confronted with transition and adaptation. Awareness on urban environmental quality is leading the vision about the built environment's resilience and sustainability, highlighting the importance of a multidisciplinary framework for urbanisation processes. One of the main concerns is the negative impact of outdoor noise due to road traffic, whereby controlling the sound environment through good quality spatial production is a priority. Europe and other parts of the world are experiencing a chronic traffic congestion problem. The environmental impact of this situation is overwhelming, where 90 % of the health impact due to noise exposure is estimated to be caused by road traffic noise. In this regard, noise maps are seen as a powerful tool in the development of new urban areas, where its noise level underestimation can endanger the wellbeing of citizens. At this rapid urbanisation, divided pronouncements on decision-making are devastating. The aim is to overcome negative aspects derived from a late intervention by including urban sound planning as an opportunity to the user's experience and wellbeing, avoiding poor patches in the urban configuration and economical burden. The present work is committed to the development of tools for controlling, communicating and designing the sound environment on a level beyond today's solutions, capable to be included at the early stages of the planning process. First, the study goes through the importance of the *quiet side* and the implementation of an engineering method as a powerful tool in the urban development, obtaining accurate results compared to measurements. In an attempt to study time variations of traffic within cities and its relevance regarding noise emission (normally overlooked in current noise mapping calculations), a microscopic road traffic modelling tool is developed in the second study, giving useful output for noise level predictions as function of time. The time-pattern analysis opens the possibility to test traffic configurations and explore a large variety of results in the form of descriptors as statistical indicators, calm periods and noise events, and outcomes as difference maps and contribution maps. The third study extends toward the evaluation of the effects of spatial heterogeneity (considered a key strategy to increase the liveability of spaces) on the environmental performance and resilience capacity of the transportation system through the study of noise pollution and its economic impact. The studies presented are using real case scenarios as a test-bed not only for implementation, but mainly for the development of tools.

Keywords: Urban sound planning, traffic dynamics, quiet side, urban systems, prediction, road traffic noise, modelling.

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List of Publications

The introductory chapters presented here are based on the work contained in the following appended papers, corresponding to the three studies developed:

Study A

Paper I

L. Estévez-Mauriz, J. Forssén, W. Kropp and G. Zachos, "Incorporation of the quiet side in noise maps," in *Proceedings of TECNIACUSTICA 2014. 45th. Spanish Congress on Acoustics, 8th Iberian Congress on Acoustics. European Symposium on Smart Cities and Environmental Acoustics*, Murcia, Spain, October 29-31, 2014.

Study B

Paper II

L. Estévez-Mauriz, J. Forssén, W. Kropp and G. Zachos, "Traffic dynamics, road design and noise emission," in *Proceedings of EuroNoise 2015, 10th European Congress on Noise Control Engineering*, Maastricht, The Netherlands, May 31- June 3, 2015.

Paper III

L. Estévez-Mauriz and J. Forssén, Dynamic traffic noise assessment tool: a comparative study between a roundabout and a signalised intersection," submitted to *Applied Acoustics*, February, 2017.

Study C

Paper IV

L. Estévez-Mauriz, J. A. Fonseca, C. Forgaci and N. Björling, "The livability of spaces: Performance and/or resilience? Reflections on the effects of spatial heterogeneity in transport and energy systems and the implications on the urban environmental quality," *International Journal of Sustainable Built Environment*, in press, 2016.

Paper V

J. A. Fonseca, L. Estévez-Mauriz, C. Forgaci and N. Björling, "Spatial heterogeneity for environmental performance and resilient behavior in energy and transport systems," *Computers, Environment and Urban Systems*, vol. 62, pp. 136–145, 2017.

Other related publications of the author not included in this thesis:

- W. Kropp, J. Forssén, L. Estévez-Mauriz (Eds.) "Urban Sound Planning ? the SONORUS project," *Booklet. Chalmers University of Technology*, 2016.
- L. Estévez-Mauriz, S. Alves, J. Forssén, W. Kropp and J. Scheuren, "SONORUS Urban sound planning project and test sites: an example within the planning stage," in *Proceedings of INTERNOISE 2016, 45th International Congress and Exposition on Noise Control Engineering*, Hamburg, Germany, August 21- 24, 2016.
- L. Estévez-Mauriz, J. Forssén, W. Kropp and G. Zachos, "Isolating key features in urban traffic dynamics and noise emission: a study on a signalized intersection and a roundabout," in *Proceedings of INTERNOISE 2016, 45th International Congress and Exposition on Noise Control Engineering*, Hamburg, Germany, August 21- 24, 2016.
- L. Estévez-Mauriz, J. Forssén, W. Kropp and G. Zachos, "Urban space and the sound environment: transport system, urban morphology, quiet side and space users in the SONORUS project, " in *Proceedings of INTERNOISE 2016, 45th International Congress and Exposition on Noise Control Engineering*, Hamburg, Germany, August 21- 24, 2016.
- J. Forssén, L. Estévez-Mauriz, C. Torehammar and P. Jean, "A low-height acoustic screen in a setting with an urban road: measured and predicted insertion loss," in *Proceedings of INTERNOISE 2016, 45th International Congress and Exposition on Noise Control Engineering*, Hamburg, Germany, August 21-24, 2016.
- L. Estévez-Mauriz, G. Zachos, J. Forssén and W. Kropp, "Soundwalks in Gothenburg," *Tech. report 2016:12. Chalmers University of Technology*, 2016.
- L. Estévez-Mauriz, J. Forssén and W. Kropp, "SONORUS report on Göteborg Test Site including Urban Sound Planning Workshop," *SONORUS Tech. report. Chalmers University of Technology*, 2015.
- S. Alves, L. Estévez-Mauriz, F. Aletta, G. M. Echevarría-Sánchez and V. Puyana-Romero, "Towards the integration of urban sound planning in urban development processes: the study of four test sites within the SONORUS project," *Noise Mapping*, vol. 2, 57–85, 2015.

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Chapter 1

The complexity of the sound environment study

The unprecedented rate at which cities are growing, with the inevitable densification consequence in the urban development, has put high demand on the current and the future production of space. Complying with that demand has become a priority in the urbanisation process. However, the urgent process has enormous consequences on the urban environment, the sustainability and the resilience capacity of our cities. On the other hand, citizens are demanding as well higher qualities for their surrounding environments. With all this in mind, today's urban development needs a constant strategic solution capable to understand and include the relations between the urban form, the environment and the urban life.

In this sense, the embracement of multiple disciplines is required, expanding the limits, e.g. of urban planning, design, traffic planning, environmental and social studies. The expansion requires a transformation into a complex analysis composed of multiple interconnected systems. The urban form might appear as a constraint, imposing boundary conditions, forcing the systems to lower their performance and/or their capacity to adapt. Examples of this might be the energy consumption performance, the outdoors environmental quality, the connectivity and mobility patterns, etc. Understanding that the *compartimentalisation* of cities constrains the possibilities to supply with the increasing urbanisation and the demanded qualities, the urban form can also be an opportunity to improve such space quality by following Hillier's words: 'Good space is used space' [30].

In the reciprocal influence between urban form and urban life, the environmental qualities are normally the ones of the overlooked. They normally come very late in the city planning process, mostly when complaints or problems appear, or when regulations forces them. One of the main reasons for this is that the main human interaction with the city is through seeing, and invisible pollutants that are perceived through other senses are becoming of less importance. However, the inclusion of air quality in the study of the built environment has become more pronounced in the last decades. Unfortunately, the acoustic quality has not followed the same trend. In the future, noise pollution can become the first environmental cause of death.

Either way, the experience of a place is made through a multi-sensorial approach, and the auditory perception is part of it. Active users in cities are the main actors shaping the environment, influencing our social behaviour. A greater coherence between auditory and visual design is demanded to understand the space. In this sense, the improvement of the sound environment is strongly connected to the urban morphology. The idea is that we overcome the negative aspects derived from a late intervention and approach to this interaction as an opportunity to the user's experience and wellbeing within the production of space. In this way, the activities and functions rely on a certain appropriateness of the sound environment. The liveability of a residential area or a park is incomplete if the sound environment is incoherent with the intentional use of such space. Thus, the sound environment is relevant to the liveability of spaces, to what spaces can afford in terms of sound environment quality.

1.0.1 Spatial morphology and the sound environment

Through the urban design, we give form and structure to our society, to the quality of places. In this sense, the built environment is an extension of us, which allows such liveability.

In the study of urban form, all urban morphology schools based their studies in three principle elements as Moudon pointed out [43], the form, the scale and the time. Regarding the form and its patterns, they are defined by the physical elements with a capacity to persist, such as the buildings and their related open spaces, plots-lots, and streets. The second one is the resolution or scale, where a scale is permeated by the rest, going from the building/lot to the street/block, the city, and the region. The last one is the time or process, where the built environment is under constant evolution, subject to socio-cultural, but also socio-technical, and environmental forces that transform and adapt the elements composing the city. To improve the liveability of spaces, we must understand these three elements and their interaction, as they are the foundations on which the functional aspects are based. The function does not have a capacity to persist (in principle), and it is submitted as well to the demands and transformations resulting from social, technical and environmental changes.

The interaction between elements that compose the built environment [49] (the land use, the buildings, the public spaces, the urban layout and the topography/land), influences the relation between space and society, both in the human-human and the human-environment relation [42]. A hierarchy of influence can be found among the built environment elements, impacting on the sound environment. For example, changes in the urban layout regarding traffic design or a change in the public space have a great capacity to transform (among other aspects) the sound environment and its perception.

Nowadays, urban spaces are becoming extremely similar. However, in the visual aspects, uniqueness and recognition is the most wanted experience (I do not want to mean uniqueness as *out of context*). If the user experience and the function of spaces is of relevance, then the urban moments demand their own signature [3]. We must persuade unique experiences, unique appropriateness, unique sound environments. In this regard, the changes and interactions between the built environment elements have the capacity to inform, detect, recognise and moreover, to be meaningful as well to the auditory experience [27].

1.0.2 The risk of missing the opportunity: inaction and co-productive action

Co-productive actions are needed in the rapidly changing built environment, where street networks and the public space will become essential to compile with the increasing demands of sustainable means of transport. We need to be able to 'diagnostiquer le bien' as Amphoux said, to diagnose the good qualities [2] to be able to promote favourable conditions for sounds in the public space. As Gauthier and Gilliland stated, the main contribution of urban morphology, regarding the study of cities, is on acknowledging a way to understand the built environment through 'a system of relations submitted to rules of transformation' [28]. The disconnection of urban systems in the urban planning process may increase the pressure on the urban environment and threat people's health and wellbeing. Landscape fragmentation and transport emissions are examples of triggers of the environmental pressures present in urban development processes [18]. It has never been more important for social, technical and ecological systems to work together.

1.0.3 Urban systems strategies and the sound environment

The transportation system is considered as the main responsible agent for the breach of the air and acoustic quality recommendations within the built environment. Ensuring liveability that allows environmental benefits [15] is becoming a battle-ground between socio-technical and socio-ecological perspectives. The environmental impact has increased the pressure on new approaches within urban planning [57] and on environmental policies. For example, strategies towards the increase in spatial heterogeneity are becoming stronger as a way to improve services and reduce travel distance, providing higher levels of liveability [61]. However, liveability might be constrained by the inefficiency of such approaches, and urban pattern trade-offs might be necessary.

1.0.4 Impact of transport on the sound environment

Traffic noise, air pollution, disruptive events and poorly planned places within our cities are a direct threat to our health and wellbeing. Facing this challenge requires, among other aspects mentioned above, well-planned infrastructures. Improving people's mobility within cities is a demand which have consequences on the transportation networks and modes. It is very likely that the noise pollution and its impact on citizens will rise. In this sense, the EU has started to recognised excessive noise as a large environmental health concern. About 40 % of the population in the countries within the EU is exposed to road traffic noise at levels above 55 dBA. One third of the Europeans are annoyed by noise during daytime and 20 % suffers sleep disturbance at night due to traffic noise [60].

A mono-functional view of the city is not valid anymore, and the integration of urban and transport planning is fundamental to assure efficient and liveable cities.

1.0.5 Urban sound planning

The increasing awareness on environmental quality is highlighting the importance of a multidisciplinary framework of the urbanisation processes. Within the concept of urban sound planning, we attempt to go beyond the current main objective of an acoustic intervention: the use of regulations as a noise ceiling. This approach holds restrictions in both space, as it includes the study of the most exposed receivers (generally with the main focus on the indoors), and in time, with a short-term perspective. If the concern regarding the sound environment appears only when citizens complain (or not at all), the problem will inevitably become extremely difficult to tackle whereas the cost-efficiency will be lost. The short-term and disconnected analysis in city planning, attending to isolated needs (densification, transport demands, integration, visual aesthetics, economical or political reasons) is doomed to failure.

As an example of possibilities to integrate urban sound planning in the planning process, an article that analyses the practical implementation of such approach was published by the author and four project colleagues [1]. The idea was to perform a critical analysis and a practical implementation of the urban sound planning approach. The practical implementation has to be based on a comprehensive contextualisation, using the appropriate methodologies. Moreover, to be part of the urban planning process, innovative solutions are needed, not only in technical aspects but also in the interaction with the stakeholders. This aspect has been shown as a constraint for the research process (lack of information, not being part of the decision process), and it also results in a failure of the effective implementation of the tools and results.

1.0.6 Bridge the gap – tools

A further enhancement of the planning process is demanded, however, not possible if the visions regarding the urban planning are fragmented.

The aim is to include urban sound planning in the planning process of cities at the earliest stage. For this, the present work is committed to the development of tools for controlling, communicating and designing the sound environment on a level beyond today's solutions, capable to be included at the early stages of the planning process.

1.1 Thesis structure

The licenciate thesis is structured in five chapters. The structure responds to the research development of interests, interactions and findings. The present chapter addressed the overall concept in which the research has been carried out; the urban space and the sound environment – bridging the gap between future urban practice and the current situation in cities, through the development of tools in a trans-disciplinary study.

The **first study** aims at including an accurate tool in noise mapping techniques to respond to the evaluation of restorative sound environments enabled by inner-yards. The results of this study are presented in detail in Paper I and a brief justification as well as some added results are summarised in Chapter 2.

However, noise-mapping techniques are also failing in the study of traffic dynamics, of importance to assess not only annoyance, but also appropriateness of the sound environment to a place. The **second study** develops a dynamic traffic noise tool to study traffic dynamics and its effect on the sound environment. A deep explanation of this can be found in Papers II and III, with a small introduction in Chapter 3. Within this study, the work was carried out for the Frihamnen test site in Gothenburg, Sweden. This test site was one of the four study cases within the SONORUS project.

The **third study** contains the work carried out within the urban form and the environmental performance, in an attempt to study the urban environmental quality form a multi-disciplinary point of view. Chapter 4 gives an initial description of the process behind the study, and Papers IV and V present both the theoretical background and the implementation of this type of approach.

The last chapter is dedicated to presenting a brief discussion and ideas for future work. More details about the different studies can be found in the appended Papers.

Fig. 1.1 intends to give an overview of the concepts and the studies that constitute this work. Both first and second studies correspond to the work carried out within the SONORUS project, while the third study is the result of the work developed during the IDEA League doctoral school on Urban Systems. All of the studies presented are using real case scenarios as a *test-bed* not only for implementation, but mainly for the development of the tools.

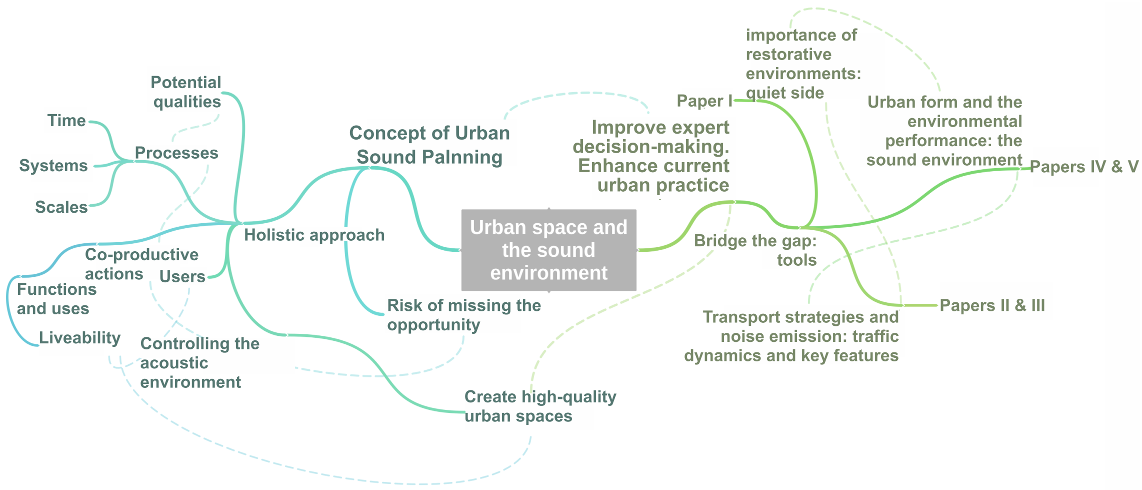

Figure 1.1: Overview of the concepts and interactions present in this study regarding the urban space and the sound environment.

Chapter 2

The importance of restorative environments: the quiet side in noise mapping

The first paper carried out within this research work (Paper I) raised from the importance of the study of noise restorative places such as the inner-yards. The inner-yards constitute a powerful tool in the development of new urban areas, as the regulations consider them as part of the limitations (or opportunities). In the increasing densification process, especially in cities as Gothenburg, this type of construction is relevant, and accurate and efficient tools are demanded to properly assess the noise levels at these places. In Paper I, the *Qside implementation model* was developed and tested within real case studies.

2.1 Introduction

During the 70s, the increasing concern for the environment led to the study of environmental services or ecosystem services, as the contributions from the ecosystems to the well-being of people. Within this approach, the intention has been to reduce the negative environmental impact. Regarding noise reduction in Europe, the development of legislation has been decisive, especially with the appearance of the END, the European Noise Directive. The intention within this framework is to 'avoid, prevent or reduce the harmful effects of noise on human health' [19] from several noise sources, including road traffic. To achieve this, a common approach regarding the management of noise within Europe is needed. The main demand is the study of agglomerations through noise maps. In order to cope with such a demand, noise prediction software have been developed, incorporating different calculation methods, e.g. Nord2000, NMPB–Routes, CNOSSOS-EU, Nordic Prediction Method, ISO 9613. However, these methods underestimate the noise levels found in the courtyards [38]. The principal attempt of such methods was to calculate the noise levels at the most exposed façade, while the shielded areas were of less interest. For the inner yards, the influence of multiple façade reflections is important to estimate the noise levels. Nowadays, the previous common noise mapping techniques are nonetheless used to study the noise levels at such spaces. These areas are known as the ones not exposed to sound pressure levels above a certain magnitude [17]. The shielded façade is introduced as the quiet side, becoming more and more popular since its identification as a common restorative place to moderate the adverse effects of road traffic noise [19].

In this regard, noise maps are seen as a powerful to allow or decline the construction of new buildings. They are becoming more relevant in the decision-making process, being then part of the resulting model of the city, where its underestimation can endanger the well-being of citizens and residents. The densification argument of consolidated cities is giving a lot of power to the quiet side concept regarding the development of new urban areas and the consolidation of current ones. Traditionally, legislation is based on limit values for the most exposed façade, however, this trend has been changed, since the decreasing of levels at this façades can become extremely difficult. In this sense, the quiet area concept has been welcomed from the annoyance perspective, as a powerful tool to reduce it. In this sense, the possibility to accomplish reduced noise levels at the most exposed façade becomes difficult and expensive [37]. For example, the guideline value in Sweden regarding the $L_{Aeq,24h}$ is 55 dB [44]. However, the new rule from 2015 raised this level to 60 dB in the case of new small flats (up to 35 m^2). For any other flat size, no level limit is applicable as long as a maximum of 55 dB is reached on the quiet side for at least half of the rooms considered as living room or bedroom.

2.2 Aim

Accurate models capable to calculate the multiple façade reflections have been developed, as the application of the finite-difference-time-domain (FDTD) and the pseudo-spectral time domain methods (PSTD) [31, 54]. The computation time is a drawback for these methods. Having this in mind, an engineering model, known as *Qside model* was developed within a previous project [55] with the intention to obtain reliable results to predict the noise levels at the shielded areas at a low computational cost, where calculations can be incorporated into the current noise mapping techniques.

The input for the model is mainly on geometrical parameters, such as the width of the canyon street, the height of buildings, the distance from source to the top edge of the building, etc. In the research presented here, the developed model [55] is extended and implemented in order to achieve a closer connection to the noise mapping software calculations, in a way that the noise levels at inner yards can be substitute by the more correct ones.

The paper presented within this topic exposes the development and implementation of the *Qside model* under real case scenarios and its comparison with noise mapping prediction software (*SoundPLAN*). The *implementation* includes an extension of the model regarding ground reflection and the development of geometrical parameters at complex situations, the effect of air absorption based on the ISO 9613-1 [33], as well as decorrelation. Scattering due to turbulence was incorporated the model based on [26]. The model also implemented the road traffic source model Nord2000.

The focus of the engineering model is on the diffraction over the buildings in both the inner yard and the street canyon geometries. When the inner yard is totally shielded (i.e. without openings or other paths not being over the roof), the *Qside implementation model* is dominating. When it is not, the reflection in the horizontal plane is contributing to a higher extent, and the calculations can be performed through noise mapping software, as diffraction from the *side* of the building is included. The *Qside model* only accounts for closed inner yards. However, approximations to closed inner yards are possible in the case that the main noise contribution is shielded by a continuous set of buildings without gaps between them. The previous case is explained in the section below, resulting in a large agreement, with 2.7 dB (L_{Aeq}) difference between measurement and implementation model.

2.3 Remarks and outcomes

The *Qside implementation* calculations were compared with noise mapping prediction calculations using the *SoundPLAN* software (see Fig. 2.2). The calculations are made for hard ground and both soft (20 % absorption) and hard façade (3 % absorption). During the implementation process, inaccuracies with the usage of soft façade were found and remarked as future work in the paper presented (Paper I). The error in the *Qside model* is mainly detectable when a soft façade is present. The inaccuracy in the attenuation within the canyon street ($A_{can,flat}$) regarding an exponential factor, resulted in an overestimation of the noise levels (replacement of ρ^2 to ρ^6), especially for the soft façade (see Fig. 2.1). The correction was advised to the developers of the *Qside model* [56].

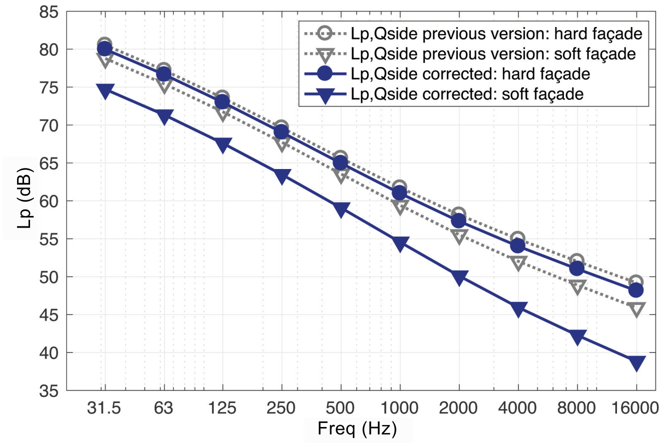

Figure 2.1: Contribution to the background level. Soft and hard façades: previous and corrected version. Line source with Lw=100 dB/m in each frequency band.

The above described error was noticed when comparison with the noise mapping software calculations were performed for the soft façade. A corrected comparison is shown in Fig. 2.2 for hard and soft façade. When the façade is considered as hard and only the first reflection is taken into account in the noise mapping software, the differences compared with the *Qside implementation* were around 8 dB for low frequencies, increasing as the frequencies get higher. When a higher order of reflections, 20 in this case, is included, the results get closer to each other, with a total difference of 4.3 dB for the hard façade and 1.3 dB for the soft one (L_{Aeq}). The large number of reflections that are needed makes it computationally extremely costly to calculate the noise levels at shielded areas for whole cities through the current noise mapping software techniques and methods.

Minor deviations are present at frequencies below 125 Hz and above 4 kHz, the latter mainly due to differences air attenuation modelling. Multiple reflections mean that the sound waves travel longer distances, and the air is then absorbing more sound energy than for the direct propagation. The *Qside model* only accounts for the direct ray source-receiver to base the air absorption, resulting in a drop at high frequencies in the noise mapping software calculation with Nord2000, leading to inaccuracies in the *Qside model* at higher frequencies (8 kHz). Regarding differences in the low frequencies, the diffraction model of *Qside* starts to fail due to the approximation of the *Qside model*. The deviation starts to get significant at 160 Hz, and gets severe at frequencies < 50 Hz. In this regard, the *Qside* is based on the Harmonoise model, which overestimates the very low frequencies [35], and the calculations within *SoundPLAN* are performed with the Nord2000 model.

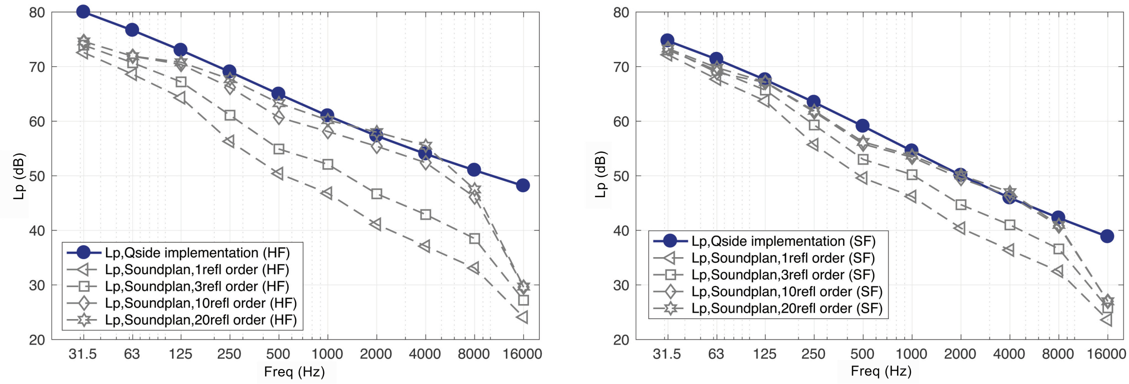

Figure 2.2: Contribution to the background level. Lw=100. Line source example. Calculations from the *Qside implementation model* and *SoundPLAN* with hard (left) and soft (right) façade

As shown in the comparison made in the paper presented (see Paper I) and real measurements in a closed inner yard, the total difference between measurements and *Qside implementation* is about 3 dBA, with very similar spectra. The noise mapping software calculation results in a total underestimation of 15 dBA using the standardise single reflection.

A further comparison was performed for a case in Partille, outside the city of Gothenburg. Noise abatement measures due to the traffic noise coming from the motorway were performed. A series of gaps between the buildings were filled with new buildings. In order to analyse the effect of this action, several measurement points were studied and gathered [25].

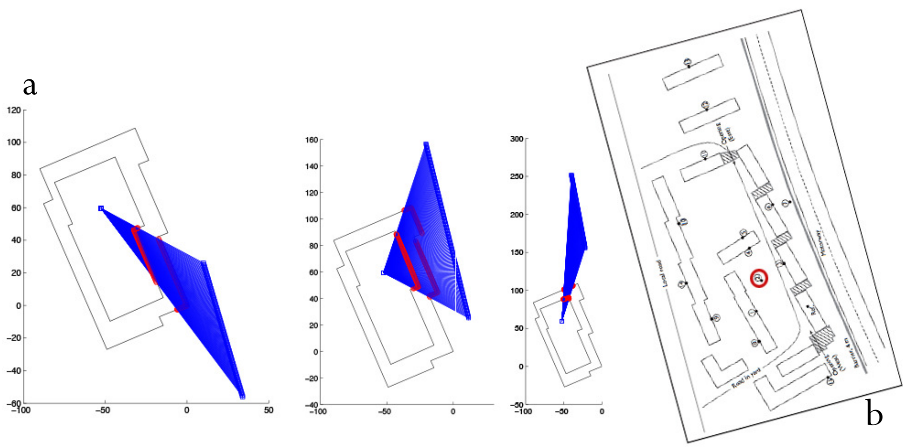

Figure 2.3: Snapshots on the *Qside implementation model* calculations (a) and the real scenario (b)

One of the measurement points was selected to compare with the *Qside implementation model*. The point was located approximately in the centre of the yard (see Fig. 2.3). The noise level resulting from the measurement was 51.6 dB (L_{Aeq}). A series of geometry simplifications were applied in the model, simulating a closed inner yard. The *Qside implementation model* resulted in a noise level of 54.3 dB, 2.7 dB more than the measurement (L_{Aeq}). This difference may respond mainly to the geometry simplifications performed in the height and shape of the buildings.

As stated above, the implementation model has certain limitations, however, due to the agreements found with BEM and analytical diffraction theory [47] (to validate diffraction and ground effect), and within the measurement comparisons, the engineering model proposed can be considered as a reliable tool to predict the noise level at shielded areas as a correction to the ones predicted by commercial noise mapping software. Further work is needed mainly regarding the automation of the process and the consideration of complex scenarios and distant noise sources, since they influence the results at inner-yards [51]. The idea is that the results from the *Qside implementation model* can be incorporated into the noise mapping prediction software.

The inclusion of such method as a prediction tool will bring further opportunities to the improvement of the built environment, whereas the access to such type of areas in the city is gaining value with its consideration as restorative places.

Within this model, the traffic is considered as a constant flow, and variations in time are not included. With this idea in mind, the following chapter (Chapter 3) compiles the investigation regarding the importance of traffic dynamics within the built environment.

Chapter 3

Transport strategies and noise emission: traffic dynamics and key features

Papers II and III address the work carried out on the topic of traffic strategies and noise emission from a microscopic point of view. Here, traffic dynamics is represented through the study of microscopic traffic simulation and noise emission modelling. The research was developed as a continuation from the *Qside model implementation*, whereas the improvement regarding tools was made for the shielded areas. However, the public areas, as sidewalks, squares, parks, etc., especially the ones located close to the noise sources, are very sensitive to the traffic dynamics we are addressing here. In this sense, we consider that there is not only room to improve the tools, but also to improve the way we communicate the information to the relevant stakeholders. Special attention was placed on developing forms of maps to better see the effect of the proposed scenarios.

3.1 Introduction

Cities are always confronted with transition and adaptation, either due to demands or needs. The 20th century demanded an adaptation of city structures to the arrival of the car. Nowadays, a further adaptation is needed (and demanded by society). Cities have in their hands numerous environmental challenges: they occupy 3 % of the land surface, host 50 % of the population, produce 50 % of the global waste, emit 60-80 % of the greenhouse gases and consume 75 % of the natural resources [52]. Within this framework, it seems that the environmental quality is of great relevance. Without it, cities can become hostile places. However, it seems that the urbanisation processes and the environmental sustainability have been under a constant collision driven by sustainability indicators as accessibility, quality, health, nuisance and mobility, etc. [50]. Special attention is to accessibility as one of the driving forces in contemporary cities to guarantee social, environmental and economical sustainability. Regarding the environment, the improvement of mobility is seen as an urban opportunity; how people use and move in cities is addressed as a way to improve liveability. The concern on improving mobility in cities is intrinsically connected to the traffic design and the transport management. But the battleground to play for this collision is normally the infrastructures. Europe and other parts of the world are experiencing a chronic traffic congestion problem. The environmental impact of this situation is overwhelming, where 90 % of the health impact due to noise exposure is caused by road traffic noise [46].

There is a need for better urbanisation configurations capable to respond to the increasing demand on wellbeing. As stated in previous chapters, urban patterns are a key for a sustainable built environment. Controlling the sound environment through good quality spatial production is a priority. The traffic design and transport management cannot afford being disconnected from the overall urban planning process. At this rapid urbanisation, divided pronouncements on decision-making are unaffordable, instead, a careful planning decision process can avoid poor patches in the urban configuration and economical burden.

A more efficient transport layout that brings opportunities to improve the sound environment is pursued. It has been shown that the negative effects of noise exposure in health and nuisance are strongly linked with time patterns, causing stress of interfered activities, sleep disturbance, cardiovascular effects and cognitive impairment (among other health effects), self-reported annoyance, speech interference, etc., [7, 8, 41, 48, 59]. For these adverse effects, annoyance has been address as an indicator in the past decades. However, this is changing towards the study of direct health effects, since summarising them on the annoyance level has not lead to any significant action from the government in the past decades [5].

In order to find a common assessment to control the sound environment in Europe, the EU legislation, known as the Environmental Noise Directive (END) [19], requires the implementation of Noise Action Plans as a plan to describe actions that the authorities have to take to reduce or prevent noise. These plans are based on the results obtained through strategic noise-mapping according to the END. The commercial noise-mapping software techniques in use consider traffic as a static traffic flow, with an average speed and a constant traffic density. This type of study is entitled to assess a macro and/or mesoscopic scale, giving as output the day-evening-night noise level. Several sources of evidence [4, 9–11, 14] highlighted that this type of assessment may lead to underestimations, whereas time patterns are strongly linked to the vehicle dynamics, playing an important role in the transport behaviour and its noise emission, interfering, as previously mentioned with outdoor and indoor human activity. With high traffic fluctuations and transport modes, as the ones present in cities, the analysis needs to be turned into a micro-scale one. The problem is not from the noise-mapping software, as their intention was to analyse the noise at the most exposed façade. Again, we are confronting ourselves with a miss-usage (or lack?) of tools to study the sound environment as part of a larger picture, the urbanisation process.

3.2 Aim

In order to understand the time-pattern fluctuations that are relevant for the suitability of human activities, as well as the overall perception of the urban sound environment, a model based on individual-vehicle characteristics as function of time is developed and implemented in real study cases within Frihamnen area in Gothenburg, Sweden. The intention is to continue developing the idea of getting the bridge shorter between current urban planning practice and the situation in cities, finding a larger agreement among decision-makers, demonstrating the need of an anticipatory planning-process, capable to analyse the decision-planning-consequences.

Adding case scenarios is making the work more realistic as several constraints are present, e.g. the demanded traffic flow, the spatial limitations, etc. Paper II is focusing on the development of the tool with Frihamnen area as the test-bed. With the intention to improve the tool and study the potential of it, Paper III uses a very specific scenario planned as well for Frihamnen: an intersection comparison between a crossing and a roundabout.

3.3 The tool

The tool attempts to study the sound environment through the analysis of road traffic noise emission computed from single vehicles as function of time. It is based on individual-vehicle characteristics (speed, acceleration, driving behaviour, type). This model considers a flat city scenario and it is focused on the study of relatively small areas. This way, the main characteristics can be described in a simplified way. The tool has two parts:

- The microscopic traffic simulation giving as output the position, speed and acceleration versus time of each vehicle, using traffic simulation software (*Vissim*).
- The developed *Matlab* scripts that take the results from the first part and compute the source strength as function of time for each vehicle, incorporating the CNOSSOS-EU noise emission model [36]. The tool includes as well sound propagation modelling based on a flat city configuration.

This type of methodology based on time-pattern analysis gives the possibility to explore a large variety of results in the form of descriptors as statistical indicators, probability density functions, calm periods and noise events, and, in the form of visual outcomes as the difference and contribution maps. The tool analyses the noise emission of different vehicle types (heavy, medium-heavy and light vehicles), as well as combustion engines and pure electric vehicles.

A series of figures are added in the following pages as a demonstration of the possibilities that the tool can bring to the study and control of the sound environment. The complete description of these studies can be found in Papers II and III.

For the Frihamnen area study (Paper III), a series of maps showing the equivalent sound pressure level (dBA) at the different scenarios in Frihamnen area are plotted (see Fig. 3.1).

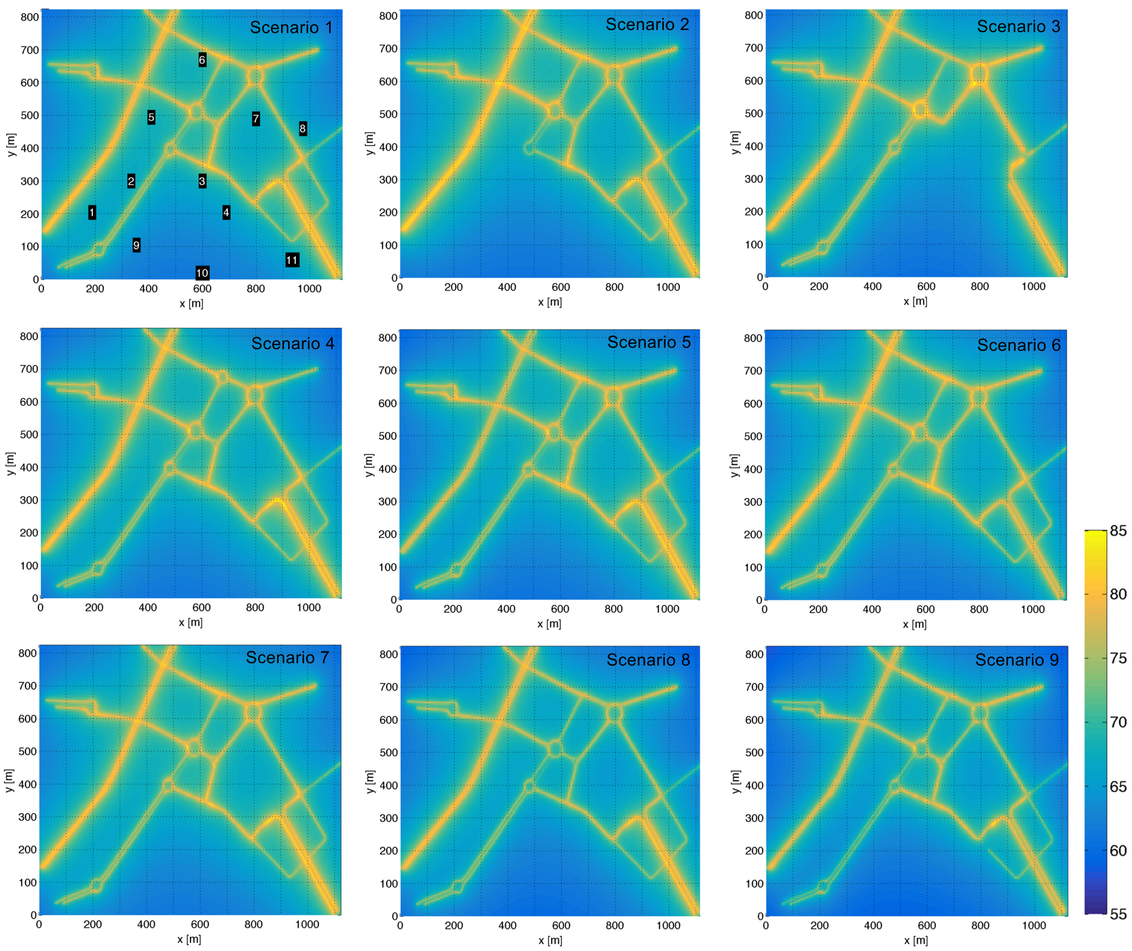

Figure 3.1: Frihamnen equivalent sound pressure level (dBA) maps at all scenarios.

For the study, eleven analysis points where chosen as a representation of different situations that can be found in the area: high traffic flow nearby, closeness to the piers, in between two roads, etc. The main condition in the developing of these scenarios was that all traffic needed to be handled in a way that e.g. vehicles traveling from A-B should be entitled to do so.

Another type of maps that can be built with this tool are the contribution maps (Fig. 3.2). This type of maps may help to better assess where the noise abatement measures need to take place depending on the indicator of interest. The maps show the equivalent sound pressure level $L_{Aeq,900s}$ that each of the road segments contribute to a certain study point. Sometimes, the relevant indicator for annoyance is the peak level. Therefore, the largest $L_{Aeq,1s}$ value during the analysis period as the L_{peak} is also studied.

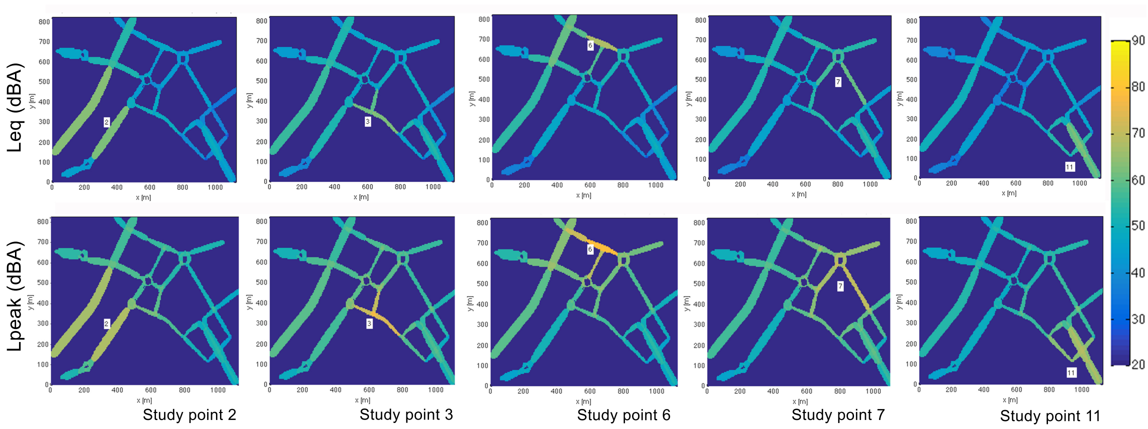

Figure 3.2: Frihamnen link contribution maps to study points: equivalent sound pressure level link contribution (dBA) on top, and peak sound pressure level link contribution (dBA) on bottom.

Fig. 3.3 shows the differences between the equivalent sound pressure level (left) at the selected scenarios and study points, and their relation with number of events (right). The largest differences between the scenarios are around 3 dB. Of relevance is the similar trend regarding L_{Aeq} at study points 6 and 7, with differences around 1-2 dB, where, at the same time, differences regarding number of events are extremely large (39-63 events in study point 6; 2-12 events in study point 7). These two study points, 6 and 7, have similar LAeq values but the former is closer to a road, thereby more likely to have time pattern fluctuations and higher number of events.

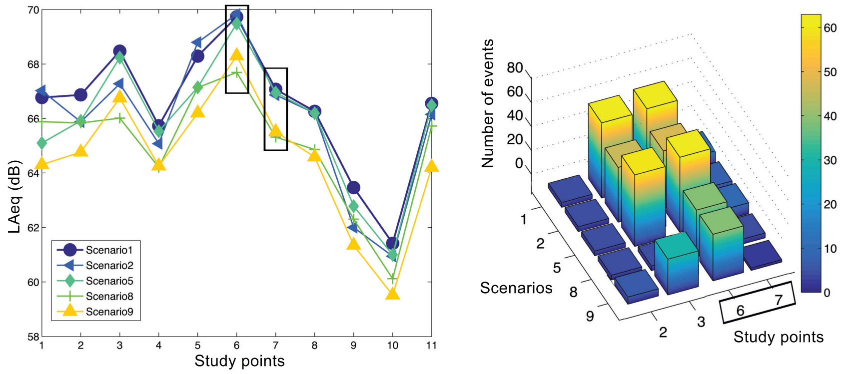

Figure 3.3: Right: equivalent sound pressure level (dBA). Left: number of events > 60 dBA.

The following type of maps were developed in Paper IV, where an intersection is studied through a comparison between a signalised crossing and a roundabout. The difference map between the two intersection types is pointing out in this case the L_{Aeq} differences between the two scenario (Fig. 3.4). The differences can be displayed for other statistical noise levels, e.g. L_{10}, L_{90}. They can be a useful visual output to study the sound environment in accordance with the human activities and building uses, for example.

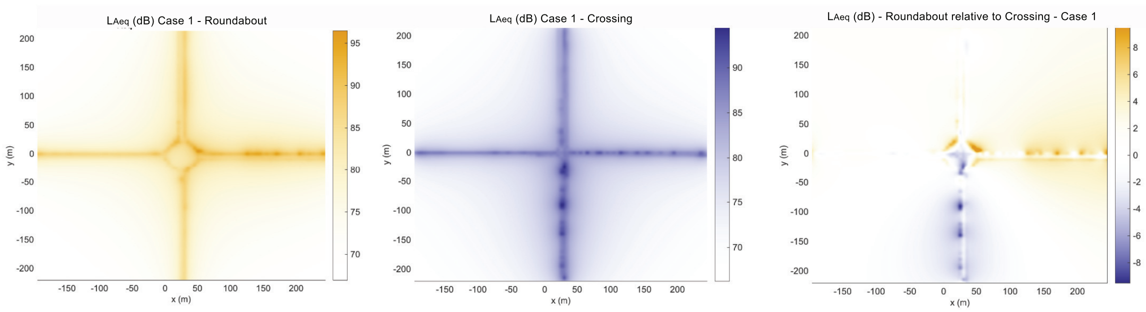

Figure 3.4: Equivalent sound pressure (dBA) for roundabout (left), signalised crossing (centre) and difference map (right).

With such tools we attempt to explore ways to improve and develop the current urban practice in cities, being capable to address how and what is relevant to explore suitability for human activities regarding the sound environment and the impact of the transport system on noise emission.

Further work regarding the tool improvement is needed, e.g. incorporating air attenuation. Going beyond the tool improvement, it can be used to enhance the study of different spatial solutions as a respond to the programmatic demands. In this sense, the relation between built and non-built space is of great relevance for the urban environment. The *Space Matrix* method [6] studies this relation through the description of the urban environment by the density variables floor space index (FSI), gross space index (GSI), open space ratio (OSR) and height of buildings (L). These variables suggest certain relations with other city dynamics, such as various environmental conditions. They are of great relevance for the quality of the sound environment as they are measuring spaciousness and boundaries. A fundamental aspect relevant for the quality of the sound environment is the source, i.e. what is on the streets, in this case. By using these density variables in combination with others such as street width, distance between road and building and road intersection type, an estimation of the road traffic sound characteristics can be performed. Using the road traffic dynamic tool developed in study B, the prediction of the source strength of vehicles as an estimation of the sound power level per unit area can be included as a variable of the quality of the sound environment, as a pattern recognition capable of improving the description of the urban environment.

Chapter 4

Urban form and the environmental performance

Cities based on a mono-perspective view are doomed to failure. Shall we urbanise by specialisation? Is this increasing the performance? What about the adaptability lost? Redundancy or diversity? Is this having an impact on the environment, on the sound environment?

Papers IV and V attempt to study the impact on the performance and resilience aspects of the environmental quality resulting from the diversification of urban form and its interactions with transport. The research was developed under the IDEA League Doctoral school[1] on Urban Systems. The aim of the school was to study how optimal conditions can be created in order to improve the adaptive capacity and resilience of cities within a trans-disciplinary view.

The urban form of the contemporary city has been subjected to debate on several research fields. Towards our concern, the city is perceived as an environmental problem source crucial for the health and well-being of citizens [18, 34], without which, cities become hostile places with no chance to improve the environmental performance through space optimisation [53]. The inevitable densification process, concentrating people and, very likely, economic activities, results in environmental pressures on e.g. air and acoustic environments. Efficient management is pursued, as well as guaranteeing a certain adaptive behaviour. The school was a continuous reflection on the study of cities joining several fields of knowledge within the umbrella of *urban systems*.

In this case, together with three other members of the school, a common interest was developed on the capacity that the interactions between socio-ecological and

[1]IDEA League is a strategic alliance among European universities of technology.

socio-technical sub-systems has to either improve or block urban processes. In concrete, the interest lies in the capacity of the spatial heterogeneity, as a key strategy to increase the liveability of cities, to enhance or hinder the performance and resilience of critical urban subsystems such as transport and energy, and in the consequences it has regarding the quality of the environment (air and acoustic quality), and hence on the wellbeing of citizens.

The first paper (Paper IV) works as a reflection on the understanding of complexities in the built environment and the consequences that the fragmentation of urban processes might have on the capacity of the city to adapt and avoid becoming an obsolete entity. On this point, the spatial heterogeneity has been addressed as a positive property of resilient urban environments. The second paper (Paper V) is addressing the application of such framework where new trajectories of urban development are being focused on the diversification and the performance improvement. A real case of urban transformation located in an industrial are in Zug, Switzerland, is studied. Switzerland has been focusing on the development of potential models for the sustainability development of the country, starting with the reduction in energy consumption and emission per person per year, known as *2000-Watt/1-ton* CO^2. To study the possibilities of the area, a series of workshops at ETH Zurich, including researchers from engineering, sociology, architecture, psychology and representatives of the industrial area, Siemens in this case. The study looked at developing prototypical patterns of sustainable development, focusing on four future possible scenarios capable to respond to environmental challenges. The scenarios accounted for variables as mixed-use, building typologies, mobility modes and target groups. The study cases attempt to investigate if there are opportunities or drawbacks of transforming an industrial zone into a fundamental part of the urban fabric of the city, into a liveable urban area [24].

In the present research, a step further is taken establishing an approach to identify relationships between key performance indicators (KPI) within the air and acoustic quality as result of the energy and transportation systems and the spatial heterogeneity. Integrated existing methodologies regarding urban and environmental studies are applied.

4.1 Introduction

Undergoing changes in social, economical, urban and climatic conditions has raised the pressure to find better ways of building sustainable and resilient urban environments. However, the built environment is composed of a series of systems, subordinated to each other. In this sense, the urban environmental quality is conditioned, to a large extent, to the comprehensive understanding thereof from a multidisciplinary point of view. Disconnected urban systems and divided pronouncements about the decision-making planning process may overlook the complexity of retrofitting, increasing the cost as a result (see Fig. 4.1). Additionally, it raises the pressure on the environmental quality, risking people's health and wellbeing, and hence, our quality of life.

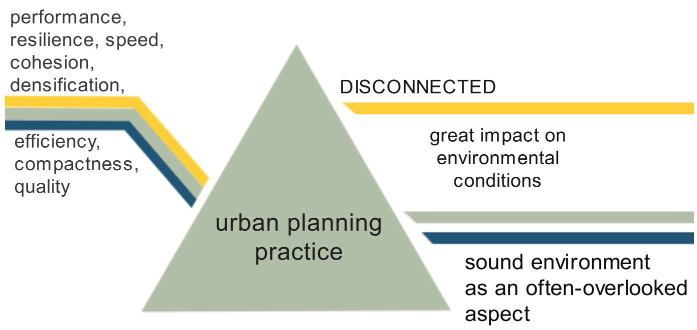

Figure 4.1: Urban planning practice disconnection.

Under this complexity vision, spatial heterogeneity is seen as an opportunity to allow the diffusion of risks, developing a suitable environment. Spatial heterogeneity is seen as the characteristic of a certain spatial process, where its intensity varies (e.g. land use). However, it can compromise the performance of systems such as transportation, water, etc.

4.2 Aim

Diversity is seen as a key strategy to make our cities more adaptable to the unpredictable changes that may occur. Meanwhile, the concept of liveable urban areas has to be satisfied. On the other hand, a sufficient level of performance of their underlying infrastructures and systems is demanded. At this juncture, the interest lies in how spatial heterogeneity affects the performance of urban systems, how it affects resilience, and, consequently, the quality of life of people. Finding the appropriate balance between performance and resilience demands a holistic thinking through the influencing variables.

The spatial development of the cities is essential to guarantee such liveability and to allow environmental benefits. Two of the main systems degrading the environment are the transportation and the energy systems. In this sense, the mobility patterns and traffic design impact directly on the acoustic environment, diminishing the liveability capacity and the resilience behaviour.

Transport is seen as the main agent to diminish the environmental quality in cities. In this sense, it has been concluded that the major contributor to the environmental noise in urban areas is the road traffic [46]. Moreover, it is one of the main contributors to greenhouse gas emissions [12]. Traffic noise generates close to 1.5 billion CHF of costs per year, accounting for direct damage on health and other negative impacts, e.g. property value [23]. For example, a mono-functional area might be more efficient to handle from the environmental point of view, as the activities and functions performed are the same, as well as the noise level targets. In the short-term, this can be a feasible area to bound, to control, but in the long-term it can bring up collateral problems as an increase in transport, leading to high levels of noise in a larger area, decreasing quality of life. The transport system is an essential part of this complex systems universe that forms the built environment. The spatial process is a (co)dependent variable of the transport system, constraining or assisting each other.

4.2.1 Some notes on the method

The study on the role of spatial heterogeneity in the environmental performance and resilience of a future urban area is studied, in this case, an urban area under transformation. The work carried out by the author of this Licenciate thesis was on the parts regarding the theory argumentation, the urban variables and the ones corresponding to the evaluation of noise pollution (performance and resilience indicators). The study regarding energy aspects was developed by one of the co-authors of the papers.

The study by Fonseca et al. [24] is expanded in Paper V in order to evaluate the effects of spatial heterogeneity on the environmental performance of energy (GHGE, CO^2) and transportation (noise pollution) systems and their resilience capacity (reserve and potential margins). The study focus is on the assessment of the performance of future urban scenarios for an industrial neighbourhood located in Zug, Switzerland (see Fig. 4.2). The current scenario has been targeted as a highly pollutant one, and transformation possibilities are explored. For this purpose, four different scenarios were studied, apart from the current one, named status-quo (SQ): Business-as-Usual (BAU), expanding the concept of an industrial area adding residential use; High-end Business (HEB), with high-rise buildings in the service sector leaving the industry out of the area; Campus (CAMP), with a university campus area, housing, catering areas, keeping industrial production in place; Urban Condenser (UC), balancing the residential, industrial and commercial uses with small local businesses.

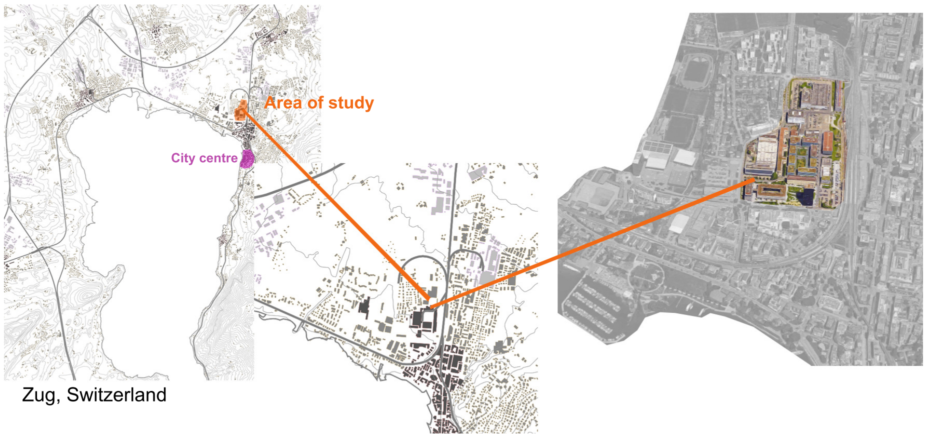

Figure 4.2: Area of study in Zug, Switzerland.

The main data gathered from the project developed by [24] was the urban configuration, the number of inhabitants (families, students), workers and visitors at each scenario. The current traffic and railway data (number and type of vehicles and railways per hour) were gathered through documentation from the Swiss Federal Office for the Environment [21, 22]. To calculate the prognosis of road traffic data, the proportion of people at each scenario traveling by private car, the number of occupants and the amount of travels per day (residents, students, employees) was accounted based on the data from the project [24]. Moreover, data on the number of inhabitants and workers per building have been included. For the purpose of the study, an estimation of the location of flats and size was needed. This was made according to the geometry of the building, the location of entrances, the building typology and the occupants. The data were included in the GIS modelling and later on exported to perform the noise calculations into the noise mapping software *SoundPLAN*. The target values were obtained from the Swiss Noise Abatement Ordinance [32].

To analyse the environmental performance, a series of acoustic indicators were studied. The reason why these indicators were chosen is due to their representativity to study the sound environment and to their intrinsic links to the urban configuration, e.g. area exposed to noise, people exposure, quiet areas, etc. (Table 4.1).

Indicators: noise pollution evaluation		
Id	Description	Measuring
ONE_{Ld}	Outdoor area exposed to noise during the day	m^2
ONE_{Ln}	Outdoor area exposed to noise during the night	m^2
QA_{Ld}	Quiet public areas during the day ($\mathrm{L_{Aeq}} < 45$ dB)	m^2
EO_{Ld}	Outdoor users exposed to noise during the day	people (all)
EO_{Ln}	Outdoor users exposed to noise during the night	people (all)
IE_{Ld}	People exposed to high noise levels during day (indoors)	people (all)
RHA_{Ldn}	Residents highly annoyed by noise	people (residents)

Table 4.1: Indicators to evaluate noise pollution. All results given in percentage.

Moreover, the total number of residents indoor exposure (L_{d}, L_{dn}) and the total number of users exposed to both indoor and outdoor noise (L_{d}) are included (see Table 4.3).

Environmental attributes can be included as location attributes, whereas for example, accessibility can both increase or reduce the property value of a house [58]. In this sense, decreasing the noise at the most exposed façade requires a large effort, especially in the consolidated urban areas, and the inclusion of noise studies and their interaction with other systems at early stages in the planning process, might avoid a cascade effect in the future.

In order to assess the resilience behaviour, three indicators are used to study the absorptive capacity of the transportation system, measured through the economic impact of noise pollution. Around 90 % of the health impact in Europeans is caused by road traffic noise exposure [17]. The economic impact of such exposition together with the one caused by railway noise is estimated to 40 billion €/year [46]. A reduction in the number of people exposed to high noise levels will be translated to a social cost reduction, giving a more robust and adaptive economic system. The chosen indicators were (see Table 4.2): Reserve margin of external costs due to residents noise exposure ($RM_{\mathrm{T,C}}$); Reserve margin of housing devaluation ($RM_{\mathrm{T,P}}$); and Reserve margin of land use restriction ($RM_{\mathrm{T,L}}$). The adaptive capacity is shown through the potential margin of land use restriction ($PM_{\mathrm{T,L}}$), where a decrease of 5 dBA in the noise target level is pursued. This is already considered in legislation when a new area is to be developed.

Indicators: resilience of transportation system measured through economic impact of noise pollution		
Id	Description	Measuring
$RM_{\mathrm{T,C}}$	Reserve margin of external costs due to residents noise exposure ($L_{\mathrm{dn}} < 55$ dB)	people (residents)
$RM_{\mathrm{T,P}}$	Reserve margin of housing depreciation to the total building stock value ($L_{\mathrm{dn}} < 55$ dB)	number of houses
$RM_{\mathrm{T,L}}$	Reserve margin of total costs due to noise-induced land use restrictions ($L_{\mathrm{dn}} < 60$ dB)	m^2
$PM_{\mathrm{T,L}}$	Potential margin of total costs due to noise-induced land use restrictions ($L_{\mathrm{dn}} < 55$ dB)	m^2

Table 4.2: Indicators to evaluate resilience (economic impact of noise pollution). All results given in percentage.

These indicators are further explained in the following paragraphs:

The $RM_{\mathrm{T,C}}$ representing the external costs due to residents noise exposure to road traffic noise ($L_{\mathrm{dn}} < 55$ dB) is based on the fact that in Switzerland, road traffic is responsible for over 80 % of noise-related costs [23]. If that cost is divided among the whole population, it corresponds to 128€/inh, per year [32]. With this, the costs of noise are computed as if all population in each scenario is exposed. Then, the population exposed to noise ($L_{\mathrm{dn}} > 55$ dB) and its total noise costs based on [13] are computed according to the noise exposure level from 55 to 79 dB in ranges of 5 dB. The results is then considered the current noise costs of each scenario. To assess the target value, a 75 % target was selected as the amount of money that can be spent as a consequence of noise costs, resembling the noise exposure situation in Europe, where 75 % of Europeans are exposed to noise levels below the limit values [46].

$RM_{\mathrm{T,P}}$ estimates the depreciation of housing value to the total building stock value in the scenario. A target of 100 % is set as a zero depreciation is pursued. This value is not based on any previous research, however, is derived from the concept of prohibition to obtain construction residential permits if no quiet façade is granted. To obtain it, the total number of houses affected by noise levels above the limit ($\mathrm{L_{dn}} > 55$ dB in ranges of 5 dB) per scenario is computed, as well as the total number of houses in each scenario. We assumed that each house accepts a level of 55 dB, having a total tolerance per scenario. The total residential price loss is calculated, based on a 0.5 % value loss per dB above the limit [17]. The sum of all these costs is subtracted from the total tolerance of the scenario, representing the total depreciation of building stock value in the scenario.

$RM_{\mathrm{T,L}}$ only accounts for the areas with possibilities for urban development, excluding small plots, roads, sidewalks, etc.

4.3 Outcomes and selected results

The urban planning process has become a powerful tool to define the political, social, technical and economical structures of our cities. Ignoring the need to coordinate strategies will just continue leading to major structural failures, sometimes irretrievable.

Paper IV focuses on a reflection about the implications that the tension between urban performance and resilience may have on urban environmental quality. These implications are analysed through the effects that the interaction between spatial heterogeneity (as a key strategy for urban resilience), transport and energy subsystems have on the human habitat and liveability, attending to main environmental stressors as air and noise pollution.

A case study was used to review these concepts and study the spatial heterogeneity and its impact on the acoustic environment as a result of the transport system (see Paper V). As an example, people's exposure to noise and its relation with the selected diversity indicators is discussed. Differences are found on the way data are accounted for, e.g. the number of people or the proportion of them, represented through percentage, among the total of each scenario (in Paper V, data are accounted in proportion). In the following analysis, one should keep in mind that the sample only accounted for 5 scenarios.

About the proportion that the number of people exposed to noise (L_{d}, L_{dn}) represents in each scenario, all the scenarios hold similar proportions of residents exposed to noise (20-25 % L_{dn} and 13-15 % L_{d}), except for the SQ scenario, with no residents. The same trend is found regarding the proportion of users exposed to noise outdoors (21-27 %). This means that the proportion of people exposed to noise at each scenario regarding the indicators is not drastically reduced or increased, hence, densification and increasing spatial heterogeneity may be made without increase the proportion of people exposed to noise. However, since population is varying between scenarios, the number of residents exposed to noise is sensitive to those changes, e.g. the number of residents' indoor exposure at the BAU scenario is 117, which16 % of the total residents in the scenario. At the UC scenario, this number is 254, representing 15 % of the total residents in the area (see Table 4.3).

Number of residents and users					
Scenarios	SQ	BAU	HEB	CAMP	UC
Total residents	0	730	1209	772	1692
Residents indoor exposure $L_d > 60$ dBA	0	117(16%)	157(13%)	108(14%)	254(15%)
Residents indoor exposure $L_{dn} > 50$ dB	0	146(20%)	265(22%)	194(25%)	444(25%)
Total users (indoor)	5775	3436	4796	4827	2919
Users indoor exposure $L_d > 60$ dBA	462(8%)	859(25%)	1391(29%)	1062(22%)	905(31%)
Total users (outdoor)	5521	7707	13838	11453	7003
Users outdoor exposure $L_d > 60$ dBA	1491(27%)	1827(24%)	3453(27%)	2364(21%)	1659(25%)

Table 4.3: Number of residents and users per scenario and number of people exposed to $L_{\mathrm{Aeq}} > 60$ dB.

Regarding the number of residents' exposed to noise, the diversity indicators that show a high positive correlation ($R^2 > 0.75$) where the diversity of users (D_{U}), diversity of land use (D_{LU}), and diversity of target groups (D_{TG}). The number of users exposed to noise (indoors) show positive correlations (R^2=0.45) with D_{LU}, as well as with D_{U}, D_{TG} and the diversity of mobility modes D_{TM}. The number of users exposed to noise when outdoors is not correlated with any of the studied diversity variables. When the proportion of people affected at each scenario is computed, a high correlation is found between the proportion of users exposed (indoors) and D_{U}, D_{TG}, D_{LU} and D_{TM}. It can be concluded that regarding total numbers, the interaction is found with the residents noise exposure, where a large diversity value (D_{LU}, D_{U}, D_{TG}) can be an indicator of a larger number of residents exposed. This is not the case when proportion is used, whereas the value of these diversity indicators is not possible to be used as indicator of residents noise exposure, but as indicator of outdoor users noise exposure.

Selected indicators calculated regarding the impact of environmental performance and the spatial heterogeneity, represented by the land use mix indicator (D_{LU}), are shown in the following figure (Fig. 4.3). D_{LU} is intended to quantify the heterogeneity of land uses in a certain area. D_{LU} scores ranged from 0, where there is no mixture of land uses, and only one single land use is present, to 1, where all the land uses are present equally. To have a balanced distribution of all cases, a value of 0.5 was set for the study, where half of the land uses are present. The values are mapped in an attempt to characterise their behaviour. There is room for improvement regarding labelling, however, the purpose was not to accurately define these behaviours, rather to be able to map and distinguish them in terms of their performance. For example, a scenario with a low number of people exposed to noise indoors during the day (IE_{Ld}) and a low value of diversity of land use (D_{LU}) responds to a mono-functional while *green* scenario. The label *green* is used to describe that the environmental performance is below the target values. The above is made accounting for proportion of area/population affected among the total of the studied scenario.

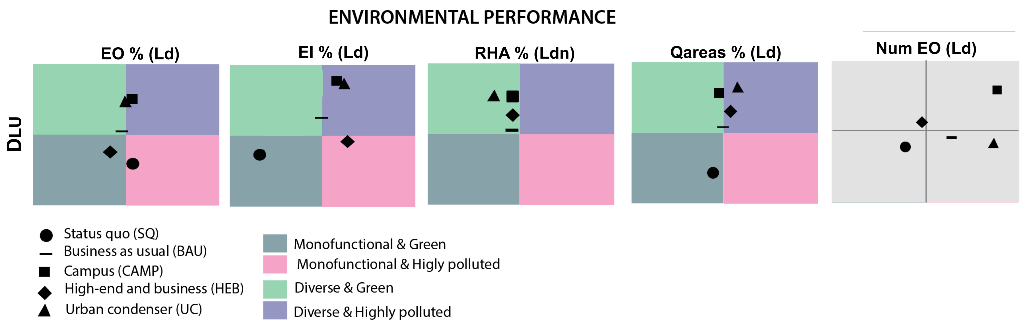

Figure 4.3: Environmental indicators (sound environment) and diversity of land use (D_{LU}).

In Fig. 4.3, the UC scenario has a good performance, with a low total number of people exposed to noise outdoors ($NumEO_{\mathrm{Ld}}$) while holding the highest diversity land use indicator (D_{LU}). A similar index value corresponds to the CAMP scenario, however, a larger number of people exposed to noise is present (2363), compared to UC(1659). Regarding quiet areas percentage, all scenarios hold similar values, however, slightly higher percentages for the ones holding higher D_{LU}. However, as previously mentioned, differences are present in the way data are accounted. In this case, data can be included as the total number of affected people. The diversity of land use (D_{LU}) as one of the diversity indicators, and its interaction with the people's noise exposure is plotted (see Fig. 4.4), and a positive correlation is found. In this sense, it is concluded that purely residential land use areas are more suitable to avoid unwanted sound and higher noise levels than having mix areas [39], however this can lead to an increase in transportation due to daily activities, e.g. commuting, shopping, etc. The previous statement is mainly an argument for the indoor noise exposure. In the present study and for the scenarios shown, it is true that a high number of D_{LU} is associated with a higher number of residents exposed (left), however, if the interest lies in the users' noise exposure, the correlation diminishes for indoor exposure (centre) and even more for outdoor noise exposure (right). It seems that the values of diversity of land use are important for the number of residents exposed, but not for the number of users. In this sense, outdoor exposure of people is generally ignored when studying health and well-being issues. Difficulties in such types of studies might be the reason, also, that Europeans spend the majority of time indoors (90 %) [16], however, it has been proven that outdoor attractive sound environments can help as restorative places that might moderate noise response [29] and probably other negative responses, e.g. stress.

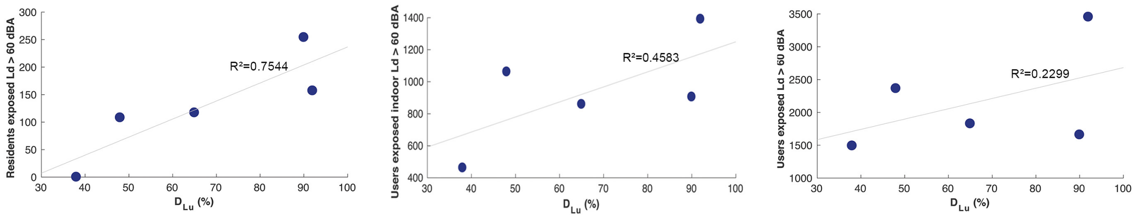

Figure 4.4: Correlation between the he number of people exposed to noise ($L_d > 60$) and diversity of land use indicator (D_{LU}). Residents (left), indoor users (centre) outdoor users (right)

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Moreover, the densities of users and residents (person/km^2) are also plotted as interesting characteristics of the urban form interacting with people's exposure to noise, both in proportion and in total number of people (see Fig. 4.5).

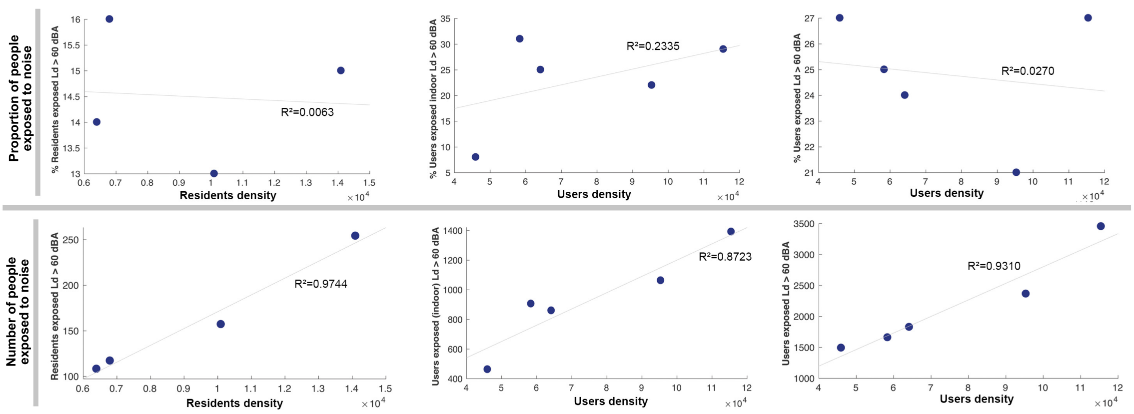

Figure 4.5: Correlation between the proportion (top) and the number (bottom) of people exposed to noise ($L_d > 60$) at each scenario and density (person/km^2). Residents (left), indoor users (centre) outdoor users (right).

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The density influence has been in the past years one of the main studied characteristics of urban form, especially in the fight between sprawl or compactness in cities (see for example [20,34,37,45]). With this type of analysis, what we are interested in is the fact that it might be cases where the traffic volume variation is not as relevant for noise impact as is the urban form characteristics. Other variables as social, sensitive, economic can impact the transport behaviour itself. In the present study, the differences between the modelled scenarios do not reduce or increase substantially the proportion of people exposed to noise at each of the scenarios, and higher densities results in similar proportions of people's noise exposure, however, it has an impact on the total number of people exposed to noise, where higher densities result in higher number of people exposed to noise.

It can be concluded that the density can be used as a parameter to indicate the number of residents and users exposed to noise, however it does not impact on the proportion of people exposed over the scenario population. Moreover, the diversity of land use (D_{LU}) and target group indices (D_{TG}) can be used as well to indicate the number of residents exposed to noise, but not the number of outdoor users exposed to noise (residents, employees, students).

Moreover, the building intensity (FAR) and its diversity (D_{FAR}) do not follow a clear trend in their influence on the environmental performance, even not on the percentage of people, public space or quiet areas at each scenario, or on the total number of people exposed or annoyed by noise. There is a moderate positive relationship ($R^2 = 0.68$) between the number of people exposed to noise indoor during day time and the building intensity, meaning the higher building.

All these differences on how to assess and study interaction are critical for the results, e.g. counting total number of people affected or counting proportion of people. This could give insights about the decision-making process and the interesting interactions regarding the spatial configuration. For example, the UC scenario, with 1659 users exposed to noise representing 25 % of the scenario users, hold a high land use diversity. However, the scenario HEB, with a high land use diversity as well, have the largest number of users exposed to noise among all scenarios, with 3453, however representing 27 % of the users in the scenario.

A further analysis than the one presented in Paper V in terms of resilience behaviour is also made for the reserve margin of housing depreciation to the total building stock value ($\mathrm{L}_{\mathrm{dn}} > 55$ dB), represented as $RM_{\mathrm{T,P}}$. All scenarios have a certain housing depreciation, however, the UC is most affected (see Table 4.4). This could possibly respond to the intrinsic characteristics of the scenario and to the fact that the scenarios are not varying substantially in their urban layout, as they try to re-use buildings and respect the major part of the traffic design.

	$\%RM_{\mathrm{T,P}}$			
Depreciation %	0.5-5%	5.5-10%	% houses affected	% housing depreciation total scenario
UC	34%	22%	56%	4.3%
CAMP	11%	9%	20%	1.3%
HEB	20%	18%	38%	3.1%
BAU	15%	12%	29%	1.9%

Table 4.4: $\%RM_{\mathrm{T,P}}$ Estimation on the reserve margin of housing depreciation (L_{dn} > 55 dB).

Moreover, a series of selected interactions within the reserve margin and the urban indicators are included in this chapter (Fig. 4.6):

- D_{LU}: within the reserve margin analysis of external costs due to residents noise exposure $RM_{\mathrm{T,C}}$ and land use restrictions ($RM_{\mathrm{T,L}}$), scenarios located at the upper left address a diverse but fragile scenario, while the upper right reflects diversity and more robustness scenarios. The differences between the scenarios are rather small in terms of reserve margin. In terms of development capacity as land use restriction due to noise exposure ($RM_{\mathrm{T,L}}$), the reserve margin in the BAU scenario holds a slightly better performance with a relatively mixed and adaptive behaviour, with a D_{LU} of 65 %. Contrary, the SQ has the lowest D_{LU} (26 %) and same land use restrictions due to noise exposure.

- D_{FAR} and FAR: the analysis is focus on similarities and differences between these two indicators, the first one related to the diversity of the building intensity (D_{FAR}) and the second one consider as an urban variable which analyse the building intensity (FAR). HEB scenario has a slightly high land restriction than the rest of the scenarios and the highest FAR. Here, the area of all buildings is two and half times the area of the plot, leading to an interpretation of a more dense area with the highest users density but the lowest residents density, and one of the lowest D_{LU} and D_{U}. This could lead to a fragile behaviour in a long-term perspective, where diversity is seen as a key aspect. In general it seems that the CAMP scenario is the one holding a high diversity of land use (D_{LU}) and building intensity (FAR) while a robust behaviour in terms of external costs due to residents noise exposure.

- Density of residents: the cost per year due to high levels of noise all four scenarios were cost is counted (SQ is excluded due to its lack of residents). Similar costs hold very different residents density, as in the case of UC, with the highest density and HEB, with one of the lowest one. The same happens in terms of land use restrictions, whereas very similar restrictions hold different densities. This means that even with higher densities, the reserve margins of external costs due to noise exposure or land use restrictions are very similar as the one at scenarios with lower residents densities. HEB scenario has 55 % less residents than the urban condenser, and the margin of costs per year is practically the same.

- Interactions between reserve margins: In this analysis, the interaction is between two reserve margins, the housing price loss ($RM_{\mathrm{T,P}}$), interacting with the cost per year due to residents noise exposure ($RM_{\mathrm{T,C}}$). A higher housing price loss implies slightly more cost per year due to residents noise exposure.

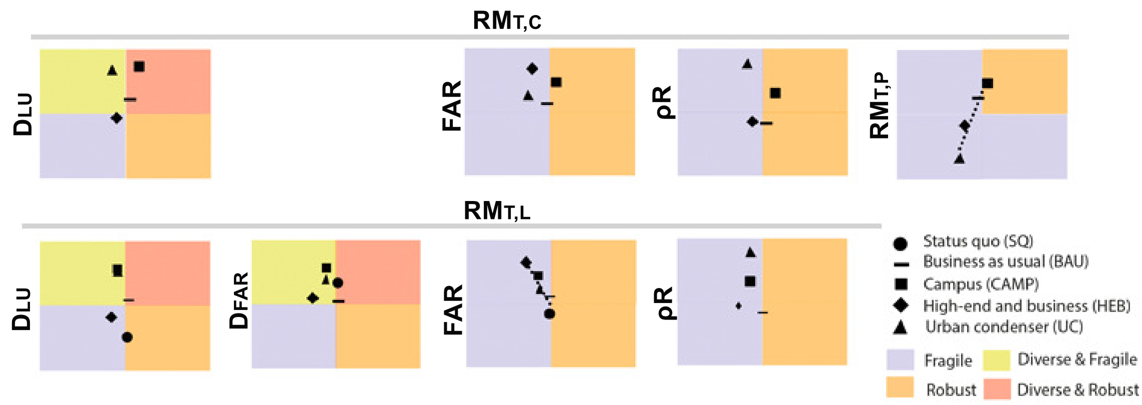

Figure 4.6: Indicators for transportation system resilience and spatial heterogeneity. Reserve margin of external costs due to residents noise exposure, $RM_{\mathrm{T,C}}$ (top); Reserve margin of total costs due to noise-induced land use restrictions, $RM_{\mathrm{T,L}}$ (bottom).

We can conclude from the tested scenarios that spatial heterogeneity does not have a clear effect on the environmental performance regarding the acoustic environment. It seems that increasing spatial heterogeneity does not go against a good performance or resilience behaviour in terms of proportion of area or people affected by noise pollution. However, certain environmental indicators regarding noise pollution are correlated with certain variables of spatial heterogeneity, e.g. the number of residents exposed to noise. In this sense, a better understanding of the tension between spatial heterogeneity and performance will support the decision-making regarding urban planning goals that could foster quality of living. Regarding the resilience behaviour, one of the studied indicators included the assessment of transportation costs due to noise exposure and its consequent devaluation as a measure of robust and adaptable scenarios. In this case, for example, diversity of land use does not present a clear influence in the absorptive capacity of the scenarios in terms of housing price loss. These outcomes might change with other set of scenarios. In general, CAMP scenario seems to be the less fragile scenario, together with the UC one. Partially reutilisation of buildings might constrain differences, as well as the influence of high traffic flow on the main urban arteries, which is not very likely to be changed among the studied area.

The validity of the conclusions is restricted by the range of the tested scenarios, however, the methodology applied can be used to study future urban implementations. Boundary conditions and scale are crucial to our assessment, whereas a change in the approach to a larger or smaller scale can give high or low degrees of response of spatial heterogeneity, which needs to be accounted for. However, this drawback was not included in the study cases, as they where studied mainly locally. A trans-scale assessment will be extremely beneficial for understanding the above described interactions. Moreover, the significance of one of the chosen environmental indicators over another is not studied, however, the interaction between them could largely enrich the outcomes of the study.

These interactions are only showing a small part of the big picture. The agents involved in the decision-making process and the production of cities are enormous. The inaction or inability to combine system analysis in the built environment study is causing the transport system to remain as main responsible for the failure to accomplish both air and acoustic quality recommendations, however, its interaction with the urban form and more concretely with the spatial heterogeneity could give answers to reduce this responsibility. These complex interactions are normally overlooked, missing the opportunities to study the problem from a broader perspective, assessing urban, social, technical, sensorial, economical and ecological aspects, among others.

Chapter 5

Discussion and Future Work

A city can truly be a city only when its streets belong to the people.

John Friedman

The built environment is changing more rapidly than ever, and the inevitable densification process is demanding a better assessment of the consolidated urban spaces, as well as the new ones. Therefore, the control of the acoustic environment through the creation of higher qualities in urban spaces is gaining more and more importance. Within this view, the support to health and wellbeing must be a priority. Our common urban surroundings and the environmental assessment thereof shall become an active part in the society. To diagnose the good qualities requires more than just an attractive image. The study of the sound environment needs to be planned carefully, going beyond today's standard approaches.

Controlling the sound environment is mainly focused on A-weighted equivalent levels which are not sufficient, since they do not help to combine different measures in an optimised way. Instead, a combination of sound level time-variation and spectral information may contribute in the study of appropriateness of the sound environment to a place, its functions and uses. Moreover, combined measures are needed to succeed in the production of space, avoiding sub-optimisation as well as unnecessary economical burden to all partners. Time-dimension and spatial scales are of importance. In this sense, there is no room for a short-term perspective. Instead, both short and long-term perspectives, trans-scale and contextualised studies are needed [40]. Acknowledging a co-productive way to interpret the built environment demands a way of thinking where transformation, adaptation, interactions, dependencies, consequences, and many more aspects, are included.

One of the main thoughts developed during this research is to achieve that urban sound planning becomes a self-evident part of the city planning, of the production of space (Fig. 5.1). We aim for a proactive urban sound planning where there is no single solution for all built environment. The synergies and combination of tools might be capable of improving expert decision-making that could enhance the current urban practice.

Figure 5.1: Overview of the concepts involved in urban sound planning, represented through a sectional layout of a city.

The public space quality assessment must include (accurate) sound environment studies capable of interacting with urban planning concepts as human activities and functionality of spaces. There is still a long way to go, however, the inclusion of real applications is probably an asset in the successful communication with all partners involved.

Study on the importance of restorative environments: the *quiet side* in noise mapping

Careful planning needs to account for accurate noise assessment results, and the access to a shielded area has great consequences in the decision-making urban planning process. In Chapter 2 and Study A (Paper I), an engineering method is further developed to study common restorative sound environments as closed inner-yards. Inadmissible deviations from actual measurements occur in commercial noise mapping software calculations. The further development of the *Qside model* intends to improve the noise mapping software calculations in this respect.

When common noise mapping calculations are performed in the modelled cases, a total underestimation reaching 15 dBA, ban be found when only the first reflection is included. When considering multiple reflections, the agreement is better, however, increasing the number of reflection in the noise mapping calculations results in an increased time consumption, being unrealistic for large urban extensions where these methods are mainly used e.g. for a whole city.

The *Qside implementation model* developed shows a good agreement with the two measurement studies within the Gothenburg area, with differences of around 3 dBA and very similar spectra. Since the model only accounts explicitly for the shortest source-receiver path, minor deviations on the implemented model are present at frequencies below 125 Hz due to differences in the diffraction modelling, and above 4 kHz due to differences in air attenuation modelling. The incorporation of the implemented engineering method in noise mapping techniques is seen as a great opportunity to improve the sound environment assessment at shielded areas as places of restoration. Further work is needed primarily in the automation process to model complex scenarios.

Study on transport strategies and noise emission – traffic dynamics and key features

Another limitation of the current noise mapping tools is that they are assuming a constant traffic flow, differing from current situations in cities. Time-patterns and vehicle kinematics are of great importance in the study of noise annoyance. In every city, all kinds of transport modes are submitted to innumerable interactions with pedestrians, traffic lights, other vehicles, as well as to different driving behaviours, etc. This fact is having a great effect on the resulting sound environment.

Study B, reported in Papers II and III, as well as in Chapter 3, aims for the development of a tool capable of incorporating the influence of vehicle kinematics using individual vehicle records in terms of location, acceleration and velocity, as function of time. The tool estimates, through a series of *Matlab* scripts, the output source strength of each vehicle as function of time. Three vehicle types (light, heavy and medium-heavy), as well as combustion engine and all-electric vehicles are included. The tool is validated for simple scenarios with noise mapping software and analytical solutions, being reliable up to 100 m from the source, as no air attenuation model is included. Moreover, it incorporates a randomisation of the sources' sound power levels in order to give results closer to the variability of measured data.

The tool is tested under real future scenarios within the city of Gothenburg, and the sound environment analysis is presented through dynamic maps and contribution maps, statistical indicators and time-pattern analysis including calm periods and noise events. It should be noted that the tool allows for other indicators to be studied than those included here. In an attempt of being as close to reality as possible, the intention was always to be able to hold the same amount of traffic as the original plan, in the studies of both Paper II and in Paper III, and the simulations were carried for the peak hour.

In Paper II, the study is focused on the overall developed of the tool within a large case study known as Frihamnen area, in Gothenburg, Sweden. Here, eight different scenarios were proposed based on the one proposed by the administration, and 11 study points were selected.

The banning of heavy vehicles or the suppression of acceleration values within the base scenario, where shown to result in moderate and very similar reductions (1-2 dBA) at the 11 selected study points. The number of events is studied as an indicator capable to evaluate interference with human activities and noise annoyance. As an example, a similar equivalent sound pressure level was found among certain study points (points 6 and 7), with differences around 1-2 dBA (6: close to an intersection and 7: close to an road with high traffic flow) for some of the proposed scenarios (1. Based scenario; 2. Removing a parallel road to the highway; 5. Speed reduction on highway; 8. Banning of heavy and medium-heavy vehicles, 9. Setting acceleration to 0). However, large differences were found regarding the number of noisy events (NE $>$ 60 dBA), reduced from 39–63 in study point 6 to 2–12 in study point 7.

The inclusion of contribution maps as a graphical tool, which is based on time patterns, is seen as an opportunity to locate conflict points. For example, transforming a crossing into a roundabout can already show a reduction in noise contribution from the nearest traffic segment. However, this demands a detailed study in order to evaluate what is happening regarding key features from a microscopic scale viewpoint.

In Paper III, a detailed study on the traffic intersection was performed, and the dynamic traffic noise tool was further developed. Here, a signalised crossing intersection is transformed into a roundabout. When modelling the peak hour scenario, both simulations are heavily congested, and the roundabout experiences serious drawbacks in terms of noise pollution. Banning of heavy vehicles was shown to be more efficient in terms of equivalent sound pressure level, in the signalised crossing. Reducing the traffic flow by 25 % within a configuration of light vehicles only was shown to give the same results expected from common noise mapping techniques in the long-term L_{Aeq} (i.e. $-$ 1.25 dB). However, when heavier vehicles are present, this reduction has an extra bonus, especially for the roundabout, with an average reduction of 2.7 dB. It can be concluded that the roundabout design is, in this case, a better option. However, a careful study regarding unbalanced congested situations needs to be addressed, as due to the principle of yielding to circulating traffic, the roundabout may perform worse than the signalised crossing for several of the indicators studied.

Regarding the number of events exceeding 70 dBA, generally, this number is lower for the roundabout intersection, however, it shows a larger variation among the selected study points. For the roundabout, the banning of heavy vehicles seemed more effective in reducing the number of noisy events.

Another graphical output studied is the difference map. For example, if all entry lanes are clustered into one, and the same for the exit lanes, the crossing intersection type is the noisier one in terms of overall sound power level. However, the roundabout exit lanes have a higher source output power as vehicles try to reach their desired speed.

The developed tool in study B can be used for estimating the sound power level per unit area as an urban environment variable, as a pattern recognition capable of improving the description of the urban environment, e.g. together with other space matrix descriptors, studying the spatial configuration as a respons to the programmatic demands.

Further work incorporating air attenuation will allow reliability at further distances. For the moment, the tool is within a flat city, and this simplification is valid for the current purpose of analysis. Coexistence modelling of electric and combustion engine vehicles is of interest. Moreover, the incorporation of autonomous cars will radically change not only the studies in transport management, but moreover, the urban layout in which these vehicles will exist.

The extension to the urban form and other system interactions is missing. In an attempt to study these interactions, Study C was carried out.

Study on the urban form and the environmental performance

Chapter 4 and Study C (Papers IV and V) analyse the interaction between systems and their capacity to improve or block the production of space, the urban resources and the liveability of a city. Urban planning has been addressed as a powerful tool to influence the social, political and economical structures. Since the urban form is not submitted to such rapid changes as function of space, the fragmented analysis of the built environment is not only causing short-term failure, but also major failures that will derive in a cascade effect through time and scale.

Spatial heterogeneity has been assessed as a positive property for resilience behaviour, however, this diversity might impact on the performance of urban systems and the resulting environment. Two of the main systems in our cities are the transportation and the energy systems, both having great implications on the quality of the built environment, e.g. the air and acoustic qualities, and hence, on the quality of life. Both have as well been known as systems highly interacting with the urban form. A theoretical framework of these tensions and interactions is developed in Paper IV. A study case with different proposed scenarios serves for the study of such tension in Paper V. It presents the previous ideas through a real case scenario subject to transformation. Four scenarios apart from the status-quo (SQ) are studied: High-end business (HEB), business as usual (BAU), campus (CAMP) and urban condenser (UC). To study the spatial heterogeneity, selected indicators are incorporated, e.g. diversity of land use (D_{LU}), diversity of floor area ratio (D_{FAR}) and diversity of building typology (D_{BT}). To study the sound environment, several indicators are selected, e.g. the share of people exposed to noise during day time, both indoor and outdoor, the share of quiet areas and the residents highly annoyed. For this case study, the spatial heterogeneity did not have a clear effect on the environmental performance regarding the sound environment.

To illustrate the analysis performed, some of the conclusions are highlighted. In general, a higher diversity does not go against a good performance. However, a higher number of residents exposed to high noise levels (Ld>60 dBA) is correlated with a higher land use mix index (D_{LU}). This is not the case when users both indoors and outdoors are accounted for. Moreover, higher densities of both residents and users are related with a higher number of people exposed to noise. However, if the assessment is made for proportion of affected people at each scenario, no correlation is found and all scenarios hold very similar percentages of people exposed to high noise levels. This could lead to different interpretations, for example, a higher density will result in the same proportion of people exposed to noise as a lower one, where by the further impact on other areas of the city will need to be accounted for, e.g. consequences of scattered or high-density urban developments in other systems, as well as the impact over time and urban scale. The change in predominant transport mode depending on the urban layout is not incorporated in the study and further analysis needs to be made in this aspect. Only the percentage of people traveling by private car is modified among the scenarios. Of the public areas among all scenarios, around 50 % are considered as quiet ones during day time.

Moreover, adaptive and resilience aspects are studied with the hypothesis that a reduction in the number of people exposed to high noise levels will be automatically translate to a social cost reduction, giving a more robust and adaptive economic system. For example, with respect to the reserve margin of housing depreciation, all scenarios have a total housing depreciation of 1–4 % (except the one without residents). The urban condenser scenario (UC) has the highest diversity of land use (D_{LU}), however, it holds a fragile behaviour regarding the external cost of noise exposure and the housing depreciation, with the largest number of houses affected (56 %). The scenario Campus (CAMP) has a more robust behaviour, with less housing depreciation and an equally high land use mix value. This means that a high diversity land use level is not giving a higher risk in terms of social costs due to noise. In this sense we can say that for the tested scenarios, robustness and adaptiveness regarding the economic impact of noise pollution, are not the result of high diversity of land use.

Further study of the urban layout needs to be considered. For example, the study of a scenario with more drastic changes in terms of geometry and spatial location could end up in more robust results regarding the interaction between spatial heterogeneity and environmental performance. To better assess the disruptive events of the modelled scenarios, the study of spatial processes in the area are needed, including time and scale aspects.

How to continue? There is plenty of room for improvement and development of the tools and approaches presented here. In the previous paragraphs selected outcomes and future work are pointed out. Detailed information can be found in the annexed papers. Moreover, finding efficient ways to converge the present studies seems to be of great relevance, i.e. a combined tool as a way to use synergy effects.

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