Thesis for the Degree of Doctor of Philosophy

Urban Sound Planning – An attempt to bridge the gap

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Abstract

Cities are constantly between transition and adaptation, where current urban development needs a consistent strategic solution capable of understanding and including the relationships between urban form, environment and urban life. Awareness of the quality of the urban environment is leading the vision on the resilience and sustainability of the built environment, highlighting the importance of a multidisciplinary urban framework. One of the main concerns is the negative impact of outdoor noise due to road traffic. Europe and other parts of the world are experiencing a chronic traffic congestion problem and the environmental impact is overwhelming, where it is estimated that traffic-related noise (including road, rail and air traffic) in Western Europe causes the loss of at least one million years of healthy life each year, where the dominating source is road traffic. The aim of this thesis is to overcome negative aspects arising from a late intervention by including urban sound planning as an opportunity for the built environment. This means including the experience and wellbeing of users, avoiding poor patches in the urban configuration and economical burden. The present work is committed to the development of tools to control, communicate and design the sound environment on a level beyond today's solutions, capable of being included in the early stages of the planning process through a holistic approach. The document is seen as a contribution to both professional practice and academic fields. In this sense, this thesis is an attempt to bridge the gap between future urban practice and the current situation in cities regarding the sound environment, through the role of sound urban planning. This is materialised from a variety of tools and approaches aimed at different spatial scales, times in planning, problems and opportunities, and fields of knowledge and contexts. First, the study goes through the urban sound planning idea and its opportunities and strategies. Thereafter, an overview highlights the threats and opportunities of urban sound planning implementation. Therefrom, the study goes into more detail about the strategies to address urban sound planning. As a starting point, the importance of the *quiet side* and the implementation of an engineering method as a powerful tool in urban development is investigated, obtaining accurate results in relation to measurements. In an attempt to study time variations of traffic within cities and their relevance with respect to noise emission (normally overlooked in current noise mapping calculations), a microscopic road traffic modelling tool is developed, giving useful output for noise level predictions as function of time. Time-pattern analysis opens the possibility of testing traffic configurations and exploring a wide variety of results in the form of descriptors such as statistical indicators, calm periods and noise events, and outcomes such as difference and contribution maps. The study extends to the evaluation of the effects of spatial heterogeneity (considered a key strategy to increase liveability of spaces) on the environmental performance and resilience capacity of the transportation system. For instance, the study of noise pollution and its economic impact gives ideas on the urban transformation possibilities when anticipatory and trans-disciplinary processes are pursued. The last study looks at the understanding and relevance of the sound environment in the use of common space. The intention is to identify suitable activities when certain sound environments and spatial characteristics are present (and vice versa), in an attempt to provide opportunities in the anticipatory design of public spaces. The studies presented use real case scenarios as a test bench not only for implementation, but mainly for the development of tools. The resulting tools developed in the thesis are: SWOT analysis of urban sound planning approach; Qside implementation model; Dynamic traffic noise assessment; Analysis matrix of indicators regarding urban form (diversity), transportation and the sound environment, studying the performance and resilience capacity; and Questionnaire about the study of common public spaces, activities and the sound environment.

Keywords: Urban sound planning, traffic dynamics, quiet side, urban systems, prediction methods, road traffic noise, citizen participation, urban strategies.

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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 developed studies:

Study 1

Paper I

Alves, S., L. Estévez-Mauriz, Aletta, F., Echevarría-Sánchez, G. and Puyana-Romero, V., "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.

Study 2

Paper II

Estévez-Mauriz, L., Forssén, J., Kropp, W. and Zachos, G., "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 3

Paper III

Estévez-Mauriz, L., Forssén, J., Kropp, W. and Zachos, G., "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 IV

Estévez-Mauriz L. and Forssén, J., "Dynamic traffic noise assessment tool: A comparative study between a roundabout and a signalised intersection", *Applied Acoustics*, vol. 130, pp.71–86, 2018.

Study 4

Paper V

Estévez-Mauriz, L., Fonseca, J. A., Forgaci C., and Björling, N., "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*, vol. 6, pp.1–8, 2017.

Paper VI

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

Study 5

Paper VII

Estévez-Mauriz, L., Forssén, J. and Dohmen, M.E., "Is the sound environment relevant for how people use common spaces?", *Building Acoustics*, vol. 25(4), pp. 307–337, 2018.

Other related publications not included in this thesis:

- Estévez-Mauriz, L., Forssén, J. and Kropp, W., "SONORUS report on Göteborg Test Site including Urban Sound Planning Workshop", *SONORUS Tech. report. Chalmers University of Technology*, 2015.
- Kropp, W. Forssén, J., Estévez-Mauriz, L. (Eds.) "Urban Sound Planning – the SONORUS project", *Chalmers University of Technology*, 2016.
- Estévez-Mauriz, L., Alves, S., Forssén, J., Kropp W. and Scheuren, J., "SONORUS Urban sound planning project and test sites: an example within the planning stage", in *Proceedings of Inter-noise 2016, 45th International Congress and Exposition on Noise Control Engineering*, Hamburg, Germany, August 21- 24, 2016.
- Estévez-Mauriz, L., Forssén, J. Kropp, W. and Zachos, G., "Isolating key features in urban traffic dynamics and noise emission: a study on a signalized intersection and a roundabout", in *Proceedings of Inter-noise 2016, 45th International Congress and Exposition on Noise Control Engineering*, Hamburg, Germany, August 21- 24, 2016.
- Estévez-Mauriz, L., Forssén, J. Kropp, W. and Zachos, G. "Urban space and the sound environment: transport system, urban morphology, quiet side and space users in the SONORUS project", in *Proceedings of Inter-noise 2016, 45th International Congress and Exposition on Noise Control Engineering*, Hamburg, Germany, August 21- 24, 2016.
- Forssén, J., Estévez-Mauriz, L., Torehammar C. and Jean, P., "A low-height acoustic screen in a setting with an urban road: measured and predicted insertion loss", in *Proceedings of Inter-noise 2016, 45th International Congress and Exposition on Noise Control Engineering*, Hamburg, Germany, August 21- 24, 2016.
- Estévez-Mauriz, L., Zachos, G., Forssén, J. and Kropp, W., "Soundwalks in Gothenburg", *Tech. report 2016:12. Chalmers University of Technology*, 2016.
- Forssén, J., Gustafson, A., Estévez-Mauriz, L., Haeger-Eugensson, M., Berghauser-Pont, M., "Prediction of quiet side levels in noise map calculations – an initial suggestion of methodology", in *Proc. of the 23rd International Congress on Acoustics*, Aachen, Germany, September 9-13, 2019.

Contents

Chapter 1

Contextualising the study of the sound environment within the urban planning process

Why is it that having a good acoustic environment in our cities so often seems to be hopeless? As acousticians we have worked for decades (since the 50's) with the sound environment. Over the years we have established guidelines, regulations, prediction methods and approaches for noise reduction.

Even in many new development or consolidated areas of cities, noise from traffic or industry leads to a dysfunctional acoustic environment, often in strong discrepancy with the intention of other aspects of the planning; living areas that do not provide the calmness that is needed for wellbeing and health of their inhabitants, parks hardly suitable for relaxation or public space in conflict with the desired uses.

As long as the acoustic environment only is considered at the very end of a planning process, if it is considered at all, it is apparent that guidelines, prediction methods or noise control measures alone are not sufficient to ensure a good acoustic environment. Therefore, a paradigm shift is needed where the planning of the acoustic environment becomes a natural part of urban planning.

In any urban development project, we have almost always the chance to do everything right from the very beginning. This is also true for the acoustic environment. In order to take advantage of that unique chance, we need to dare to include the different perspectives that are part of the urban development. However, why have we failed and continue failing so often to take this very first chance? The main reason might be the complexity of the problem and the need for a multifaceted perspective when planning the urban environment in the context of urban development projects.

As acousticians we work within our own view, which most of the time is quite narrow, trying to fix the problem from our own perspective, e.g. adding absorption to reduce noise. Today, the rapid urbanisation process is testing us every day, which means that we need to understand and learn on the way. There are many things that we have already learnt, but often they are left in the drawer. Other perspectives/views/professions are not even allowed to enter the question/problem of the acoustic environment. Of course, we will never manage to have all the relevant perspectives influencing the acoustic environment and the development process in every project, however, we must widen the approach, give the opportunity to improve, to make things better, to expand the boundaries.

If we keep on doing things as usual, we are missing the opportunity over and over again. This thesis is an attempt to include urban sound planning in the urban development process, to bridge the gap, to stop losing opportunities to make the urban sound environment good in our cities and to confront the acoustic environment from a multifaceted view.

1.1 Urban space and quality

Cities have usually been the focus of most urban studies. Historically, to be called a city, it needed to fulfil certain requirements about its physical configuration (e.g. within walls), its population size, etc. High density in cities has always been present. During the nineteenth century, over-population and over-use of resources led the cities to a crisis. However, what are the qualities that the citizens demand from the built environment? A lot of interpretations are present, as it is a question of perspective, however, a common aspect is that quality has to meet the customer's (i.e. citizen's) expectations, as Weinberg stated: 'Quality is value to some person' [1]. In this subjectivity panorama, quality needs to be related to a specific function.

History has demonstrated that 'without sufficient quality, density does not work – it even becomes dangerous' [2]. It is clear that in the last decades we have experienced gradual increase in the urbanised area per inhabitant in a global scale, beyond the limits of the city towards the urban areas. On the other hand, large urbanisation settlements have encountered a population decline: a policy report from the Lincoln Institute of Land Policy stated that between 1990 and 2000, the average built up area had a population decline in 75 of the 88 cities in developing countries, and in all 32 cities of developed countries [3]. However, in recent times, densification breaks in the urban development process as the leading factor regarding urban planning decisions, leaving in the background other fundamental aspects as the study of urban space and its qualities. Urban spaces are the backbone of every urban area: they are those outdoor places that bring people into close contact. They are the physical structure in which environmental, political, cultural, scalar and temporal processes take place. In the context of the present thesis we want to focus on the ‘urban space’ as places with enormous challenges, especially regarding the environmental aspects. Even though we talk about ‘urban space’ as a more inclusive concept than ‘city’, all along the thesis both expressions are used in parallel.

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 within the urban space. It is here where the environmental qualities are normally the overlooked ones. They come very late in the planning process, mostly when complaints or problems appear, or when regulations force them. In the case of the inclusion of the sound environment, the late appearance might be a response to the historical focus we have put on noise, looking at it from a health and wellbeing angle (for further comments, see section 1.2.2). But, certainly, it responds to the ‘progressive rationalisation of society’ that came up with the Enlightenment, setting the vision as the principal sense [4]. This rationalisation has also entered into the urban work, where the main planning interaction with the city is through seeing, and invisible pollutants that are perceived through other senses have become of less importance.

We have made tremendous efforts to reduce air pollution. Unfortunately, the acoustic quality has not followed the same trend. In the future, noise pollution can become the first environmental cause of un-health in Europe, as it seems that despite the many attempts, we have failed in reducing its effect: the period 2012-2017 has ended up in an increase of 1% of people exposed to road noise (L_{den}) [5].

A transformation into a complex analysis from different perspectives is here pursued to get profit of that chance we have within the urban development process. Understanding that the compartmentalisation of city administration 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’ [6]. For example, the liveability of a residential area or a park is incomplete if the sound environment is incoherent with the intentional use of the space. Of course, to re-do things is possible, but expensive, and most of the times, we have to cope with the existing results.

In this thesis we want to recognise, understand and get advantage of co-productive actions regarding the inclusion of urban sound planning. As Lynch [7] said, to make effective changes, we must be capable of recognising why certain fragments of the urban space are rejected and the large majority are qualified as less than satisfactory (uncomfortable, ugly, etc.). Co-productive actions are needed in the rapidly changing built environment. We need to be able to ‘diagnostiquer le bien’ as Amphoux claimed, to diagnose the good qualities [8] to be able to promote favourable conditions for sounds in the public space.

1.2 Urban systems strategies and the sound environment

The environmental impact has increased the pressure on new approaches within the urban planning [9] and on environmental policies. The notion that the infrastructures must be adapted to the physical characteristics, the needs and the opportunities that the city has, rather than the other way around, is still a radical idea. 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 [10]. However, liveability might be constrained by the inefficiency of such approaches, and urban pattern trade-offs might be necessary.

In the following paragraphs relevant perspectives are discussed: the implication of the spatial morphology, the transport system, the policies and the urban scales.

1.2.1 Spatial morphology and the sound environment

Through the urban design, we give form and structure to our society and to the quality of places. Concerning this, the built environment is an extension of us, which allows such liveability. Urban planners are the main ones orchestrating the way our city develops. Therein, all urban morphology schools based their studies in three principle elements as Moudon pointed out: the form, the scale and the time [11].

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 the physical elements, going from the building/lot to the street/block, the city, and the region, permeate the scale. 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 functions are submitted to the demands and transformations resulting from social, technical and environmental changes. These changes can be seen as other aspects influencing the city development, viewed from other perspectives, with other objectives in their agendas. However, urban planners need to attend to and anticipate such changes in every urban project.

The interaction between elements that compose the built environment (the land use, the buildings, the public spaces, the urban layout and the topography/land) [12], influences the relation between space and society, both in the human-human and the human-environment relation [13]. 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 its 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, especially in European cities, where the creation of iconic projects in the last decades, have evolved to the creation of public spaces in areas lacking of architectural distinctive projects and being subjected to marginalisation in several ways (for more information, refer to [14]). However, in the visual aspects, uniqueness and recognition is the most wanted experience (not meaning uniqueness as out of context). If the user experience and the function of spaces are of relevance, then the urban moments demand their own signature [15]. We must argue for unique experiences, unique appropriateness and unique sound environments, nevertheless, responding to the surrounding context. In this regard, the changes and interactions between the built environment elements have the capacity to inform, detect, recognise and, moreover, be meaningful as well to the auditory experience [16].

1.2.2 Impact of transport infrastructure 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. 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 [17] is becoming a battleground between socio-technical and socio-ecological perspectives. Facing this challenge requires, among other aspects mentioned above, well-planned infrastructure. Improving people's mobility within cities is a demand, which has consequences on the transportation networks and modes. As we have pointed out, it is very likely that the noise pollution and its impact on citizens will rise. The EU has started to recognise 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 dB (L_{den}), one third of the Europeans are annoyed by noise during daytime and 20% suffers sleep disturbance at night due to traffic noise [18].

How did we end up here? One of the main reasons might be the Modernist ideas in planning reflected in the Athens Charter [19] that emerged from the ideas of the 'Congrès Internationaux d'Architecture Moderne (C.I.A.M.)', held in 1933, as the concept of zoning, where the roads were conducting vehicles, not people anymore. These ideas reject the concept of city space within a human scale, killing the most primitive way of transport: walking. The human scale was practically erased from urban planning and we are still paying for it in most of the urban developments. This is where the city sound environment started to really matter, unfortunately in a negative way, with the wish to control noise, as the new ways of transport made the city a 60 km/h transport model, instead of 5 km/h when it was a pedestrian one. This radically changed the city sound environment, where the integration of urban and transport planning has been shown to be fundamental to assure efficient and liveable cities.

1.2.3 Policy instruments as leading strategy in the study of the sound environment

A great challenge is the pending issue of policies as the mechanism that every city has to use in order to achieve prosperity [20]. Policy instruments should go beyond minimum. And we, as practitioners, cannot convey the idea of building a housing area with the only goal of complying with regulations. Attached to this, specialisation in the urban planning processes has often resulted in different policies and regulations to follow, sometimes being contradictory, since they look at the city from their own perspective, scale and niche of action. Moreover, regarding environmental aspects, they ended up fractioning the polluters or the final addresses, as highlighted by Weber, et al. [21] This is probably ending up in a cascade effect of environmental, economic, social and political problems.

In order to have effective policies, they must be influenced from different angles [22], providing a combination of research, planning, incentives and learnings from the past, from successful regulations and specially from the ones that have not succeeded. Policy strategies must have a long-term approach able to make the most of the successes, to improve the current situation and to anticipate the possible challenges that arise.

1.2.4 Spatial scales in the study of urban sound planning

Studying the city (and city regions) implies studying them with its temporal and spatial scale. However, the environmental characteristics are normally overlooked, giving priority to the immediate response, oriented mainly to the economy and governance systems [23].

Scales should be seen as adaptable elements as one permeates the other in both ends. Their unpredictable behaviour is what makes them so difficult to study. Scales and density work side by side, and it is the quality associated to them that we are looking for. Human life is lived between those scales. We do not belong to a particular city scale, but we move through them without noticing it: scales do not make sense if they are not in relation to other scales [24]. The same happens to the urban sound environment.

In the study of scales and urban politics, we have moved from an expert-led planning, focused mainly on a city or regional scale, towards a participatory approach concerned about the neighbourhood scale [25]. This shift includes environmental aspects, where a participatory policy-making seems to be one of the trends, e.g. the participatory processes in the auditory environment design (see as an example the compilation of papers published under the COST Action Programme 'Soundscape of European Cities and Landscapes', 2013 [26]). However, even with this consensus-driven approach, the compartmentalisation of perspectives has failed regarding the inclusion of the study of the sound environment in the production of space.

Is the solution to break the city into more workable scales? How can we identify, learn and retain the qualities of the urban sound environment to guarantee wellbeing and sustainability? How can we work with the sound environment in order to allow for a fast built environment re-adaptation and reconfiguration demanded in the rapid pace of urban development? These are complex questions that surely need to be approached in a transdisciplinary way.

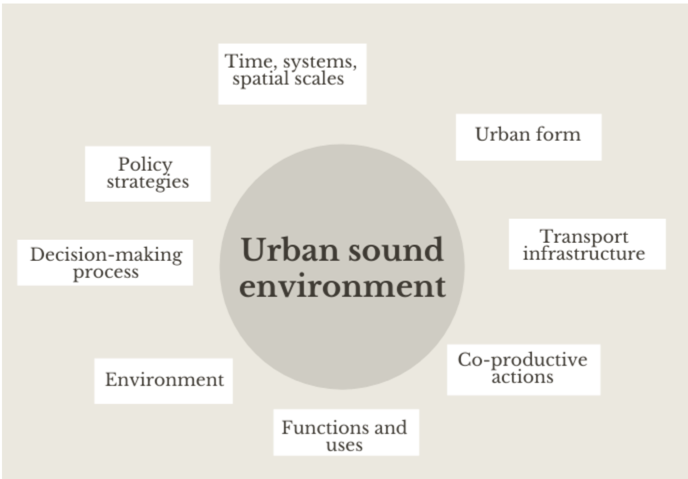

Figure 1.1: Urban sound environment: main concepts discussed in the present thesis.

1.3 Including sound in the urban planning process

Even the traditional approach to the influence of noise on health has not been capable to permeate the area of urban planning. And perhaps this, normally negative, connotation of the study of the sound environment has been the cause for this incapability. Added to it, the difficulty to include sound in the urban design processes compared to visual aspects is latent, neglecting the benefits that its inclusion might bring to the so wanted multifaceted approach to the urban planning process. In this context, an urban design is not complete if the auditory experience is not coherent with the space.

The response to this failure was probably one of the aspects that pushed the concept of soundscape, changing the focus of the study of the sound environment and its relevance. The concept appears first in the thesis by Michael Southworth [27] in 1967, conducting an experimental analysis of the urban soundscape in Boston. Despite Southworth's contributions, Schafer is known as the main contributor to the idea of soundscape studies. He argues that we need to learn to tune out a series of sounds in order to get away from the terrible noise invasion [28]. It seemed that soundscape is something you do not want and should not enjoy, rather you need to cope in the best way and try to get over it, and study it as a factor to be cleared from the city equation. This idea is still, somehow, in a large part of soundscape design; the recent international standard on soundscape (ISO 12913) highlights 'masking' techniques as one of the main components in soundscape studies [29]. Nevertheless, soundscape studies have contributed enormously to the study of the sound environment and its experiential value, especially in the last 20 years, focusing on the soundscape as the 'person's perceptual construct of the acoustic environment of a place' [30] and/or the study of the perception of the acoustic environment of a place [31]. With this approach, even after the appearance of the above mentioned standard on soundscape, several researchers have stated the facility to get lost in the terminology, the discipline appropriation and the inconsistency of the soundscape studies with the consequent challenges [32, 33]. 'What is heard?', 'where is heard?', 'how is heard?' and 'why is heard?' are important questions for human life to be lived. These questions help us to build our personal view of the city, help us to make sense of the city and of what is happening in there, make us feel part of it. The soundscape is not in the 'back' as a background noise needed to be muted, it is rather in the front of the context. However, it has been largely focused on the consensus-driven approach, rejecting the noise control management strategy, and most of the times overlooking the cross-scale interaction, the long-term perspective and the interdependency of disciplines conforming the spectrum of urban planning processes beyond urbanism.

1.3.1 Urban sound planning

The increasing awareness of 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. Such an 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.

Urban sound planning strategies might approach to the city as New Urbanism, in the way they conceived the space: to succeed, different actors have to be involved and placed in balance [34]. The success of the planning that is needed for high sound quality must pay attention to the users' experience, the context, the urban physical conditions, the scale, the environmental, the economical and the social aspects, the needs and opportunities (the resilience capacity), the diversity of stakeholders, etc. In this sense, sound quality is not fixed to the environment [35] as it evolves and adapts according to the built space and the function of the space, the users' activities and the temporal scale, to mention some of them.

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, economic or political reasons), is doomed to failure.

Urban sound planning might appear as a needed alternative, going beyond this complementary view, looking at the complexity from cross-scale interactions and multiple perspectives. This way, we might be able to analyse the urban sound environment from the spectrum of the urban planning process, which also can go beyond measuring the sound from a discomfort or preference perspective.

We need to build on the knowledge that already exists, however, we need to move towards a 'how good' perspective in the production of space; eliminating disturbing noises or decreasing the noise level is of extreme relevance in our cities, however, often not enough to make the urban environment good [36]. We need to create (more) positive impact on the city qualities starting from the planning stage.

As an example of possibilities to integrate urban sound planning in the planning process, the author and four project colleagues published an article that analyses the practical implementation of such an approach [37]. 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 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.

Urban sound planning at stake

In planning, as in any other field, time and effort constraints are present, however, much effort is put into urban planning and building design, while very little in the resulting sound environment. It is a matter of prioritisation. Urban sound planning is at stake when perspectives are not placed in balance. For example:

- Developers want their investment to be as profitable as possible. To do this, they seek to build as much as possible at the maximum price. However, they need to comply with regulations, e.g. guaranteeing a certain noise level both inside and outside of the dwellings.
- Traffic planners want traffic flow optimisation, while pursuing sustainable mobility in order to comply with regulations about noise limit levels.
- Citizens demand better quality for their cities, including the sound environment. They want to enjoy public space; perform the activities they intend to without being constrained by environmental factors.
- Acousticians' first approach is to analyse the sound environment in terms of noise regulations, minimising unwanted sounds.
- Environmental psychologists pursue better human health and wellbeing, seeking to understand the characteristics that make a sound environment more pleasant for humans, minimising the damage to their physical and psychological health.
- Politicians need to fulfil the regulatory compliance at first instance; they pursue a sustainable and safe city, meeting the needs of its citizens, as giving access to quiet areas.
- Policymakers work to guarantee a minimum common ground to build from in terms of sound quality; they need to assure a certain reliability; however, their views are particularly fragmented regarding the urban scale and agents involved.
- Urban planners are the ones trying to synthesise many urban space aspects, going beyond the analysis of the situation, trying to find patterns and rules [38] that allow for the allocation of the demanded program. Most of the times, urban planners are placed in-between the demands of the city developers, the citizens and the government, being responsible for the orchestration of the urban program. They need to comply with multiple legislations, respond to the demanded number of dwellings and areas designated to public spaces, contextualising the planned activities pursuing a good sound quality, etc. However, sometimes they do not have all the information, tools and/or support to carry this out.

In this manifold of views is where the challenge comes. We need to improve regulations and approaches, but we also need to work with the beliefs of agents and stakeholders involved in the urban planning process.

Of course, there are many other views that are missing in these lines; however, these are considered the key to our subject. If only one of these is left unattended, the risk to fail increases. We are not arguing to have a unique vision, but to have all of them evaluated, considered and aligned. At the end it is all about how you (and they) want the urban sound environment that surrounds you (them) to be; and here, we should all look to improve the user's experience. We can just generate opportunities to invite the people to use the space, as certain habitats can afford certain activities. We should create the conditions for this to happen in the unique chance we have.

A lot of effort in these views is put on the public space. To make a city work, we need to look at the public space. Public space understood as urban common spaces emerges as places of socialisation, restoration and co-creation [39,40]. It has power as it can change the way a city is perceived, how we live in it, how we feel, how we walk through it, how we socialise, etc. And it is here, in the outdoor sound environment and the public space, where this thesis focuses.

1.4 An attempt to bridge the gap – the thesis

The objective of this thesis is to offer insight on the opportunities that the inclusion of urban sound planning has in the urban processes, providing analysis mainly through pilot studies and proposing different tools adequate to the diversity of demands and targets regarding time, scale, stakeholders and context. For this, the research carried out revolves around the following questions:

- How to improve urban processes and the built environment with respect to the sound environment?
- Is the inclusion of urban sound planning of relevance for that purpose?

Further enhancement of the planning process is demanded, however, not possible if the visions regarding the urban planning are fragmented. Hereof, we present an attempt to evaluate the urban sound environment through a multifaceted perspective. The aim is to include urban sound planning in the planning process of cities at the earliest stage. This attempt is made with all respect trying to look at the urban sound environment with different interests and wishes, different tools, knowledge, goals/targets and rules, raising the following research questions:

- Which disciplines have the main needs (and responsibilities) regarding the inclusion of urban sound planning in their work?
- Can we provide tools and approaches to these disciplines?

The thesis is structured in seven chapters, responding to the research development of interests, interactions and findings. The present chapter addresses the overall concept in which the research has been carried out; the urban space and the sound environment and the role of urban sound planning – bridging the gap between future urban practice and the current situation in cities, through the role of urban sound planning.

Urban sound planning is not about one single thing, whether sound, urbanism, environment or mobility; it is mainly about relationships and perspectives (as it happens with urban planning design). The following list gathers some of the most relevant perspectives presented in the urban sound planning process through a series of papers that respond to the different perspectives and the development of tools and approaches. Firstly, it should be stressed that these perspectives were seen as research opportunities. Selecting these approaches was not a starting condition, but a consequence of the research development itself, of the interests and opportunities that were detected along the way; for example, the need for a better understanding of the consequences of noise calculation tools and legislation, or the interaction between the urban form and the transportation system, with the implications for the urban sound environment. For that better understanding, the research carried out tries to shorten or find out different paths between the enormous distance that separates, from one side, legal documents seeking to protect the city sound environment, such as the European Environmental Noise Directive (END) along with the results of the city noise maps, and from the other side, the agents involved in city planning.

- **Policy perspective:**

  The first study looks towards the practical implementation of the urban sound planning approach through a critical analysis. Paper I shows a preliminary status of different strategies carried out by the students of the SONORUS EU project and the opportunities and constraints encountered due to the different stakeholders, especially regarding regulations and policy. The focus for this thesis will be in sections 3. 'Discussion' and 4. 'Conclusions' of Paper I. Section 2, named 'Test sites analysis' is not discussed as it addresses the research carried out by a group of students (including the author) from the SONORUS project. The test site study corresponding to the author (the Frihamnen area) will be deeply explained in the Traffic planning perspective (Papers III and IV).

  Further comments about the evolution of this practical implementation and the urban sound planning concept are discussed in Chapter 2.

  - Paper I 'Towards the integration of urban sound planning in urban development processes: the study of four test sites within the SONORUS project'. *Noise Mapping journal*, 2015.

- **Perspective from noise management:**

  When we talk about noise management, acousticians are the main actors and, one of the most relevant noise topics in the EU is the inclusion of quiet areas, restorative places and the access to a quiet façade. Normally, these areas are evaluated through noise-mapping techniques; however, it has been proven that they are not as accurate as they should be. To respond to this demand, the second study aims at including a more 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 II and a brief justification as well as some added results are summarised in Chapter 3.

  - Paper II 'Incorporation of the quiet side in noise maps'. *TECNIACUSTICA Congress*, 2014.

- **Traffic planning perspective:**

  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. As a consequence, the research carried out evolved to the development of a dynamic traffic noise tool to study traffic dynamics and its effect on the sound environment, presented in the third study. A deep explanation of this can be found in Papers III and IV, with a small introduction in Chapter 4. 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.

  - Paper III 'Traffic dynamics, road design and noise emission: a study case'. *Euro-noise Congress*, 2015.
  - Paper IV 'Dynamic traffic noise assessment tool: a comparative study between a roundabout and a signalised intersection'. *Applied Acoustics journal*, 2018.

- **Urban planning perspective:**

  In this time of rapid spatial adjustments, one way to include the acoustic quality in the urban planning studies is through the study of the urban environmental quality from a multi-disciplinary point of view. The fourth study contains the work carried out within the themes of urban form and environmental performance. Chapter 5 gives an initial description of the process behind the study, and Papers V and VI present both the theoretical background and the implementation of this type of approach.

  - Paper V 'The livability of spaces: Performance and/or resilience? Reflections on the effects of spatial heterogeneity in transport and energy systems and the implications on urban environmental quality'. *International Journal of Sustainable Built Environment*, 2017.
  - Paper VI 'Spatial heterogeneity for environmental performance and resilience of energy and transportation systems'. *Computers, Environment and Urban Systems journal*, 2017.

- *Perspective from environmental / social studies:*

  However, the study of the urban sound environmental quality from a multifaceted perspective is not complete if the interaction with the users is not addressed, especially when we look at the inevitable public spatial adjustments that take place in our cities. The fifth study is based on in-situ evaluations aiming at understanding how the urban sound environment impacts on our life and how we can get advantage therefrom. For that, Paper VII pays attention to the spatial and functional characteristics of the public common space and how the sound environment affects the user experience. See Chapter 6.

  - Paper VII 'Is the sound environment relevant for how people use common spaces?' *Building Acoustics journal*, 2018.

- **Citizen perspective – Conclusion**:

  The last chapter is presented as a conclusion to the work carried out mainly through the reflection from a citizen perspective. This chapter intends to give an overview of the work carried out, its strengths and opportunities, its limitations and the impact it might have on the development of our cities and on the user experience.

1.4.1 Graphical overview of concepts and studies

Fig. 1.2 intends to give an overview of the concepts and the studies that constitute the work carried out. Papers I, II, III, IV and VII correspond to the work carried out within the SONORUS EU project, while papers V and VI are the result of the work developed during the IDEA League doctoral school on Urban Systems. The studies presented are using real case scenarios or in-situ analysis as a *testbed*; the main reason is that the development of the tools and their implementation is helped by the better understanding of the complexity within the desired multifaceted perspective.

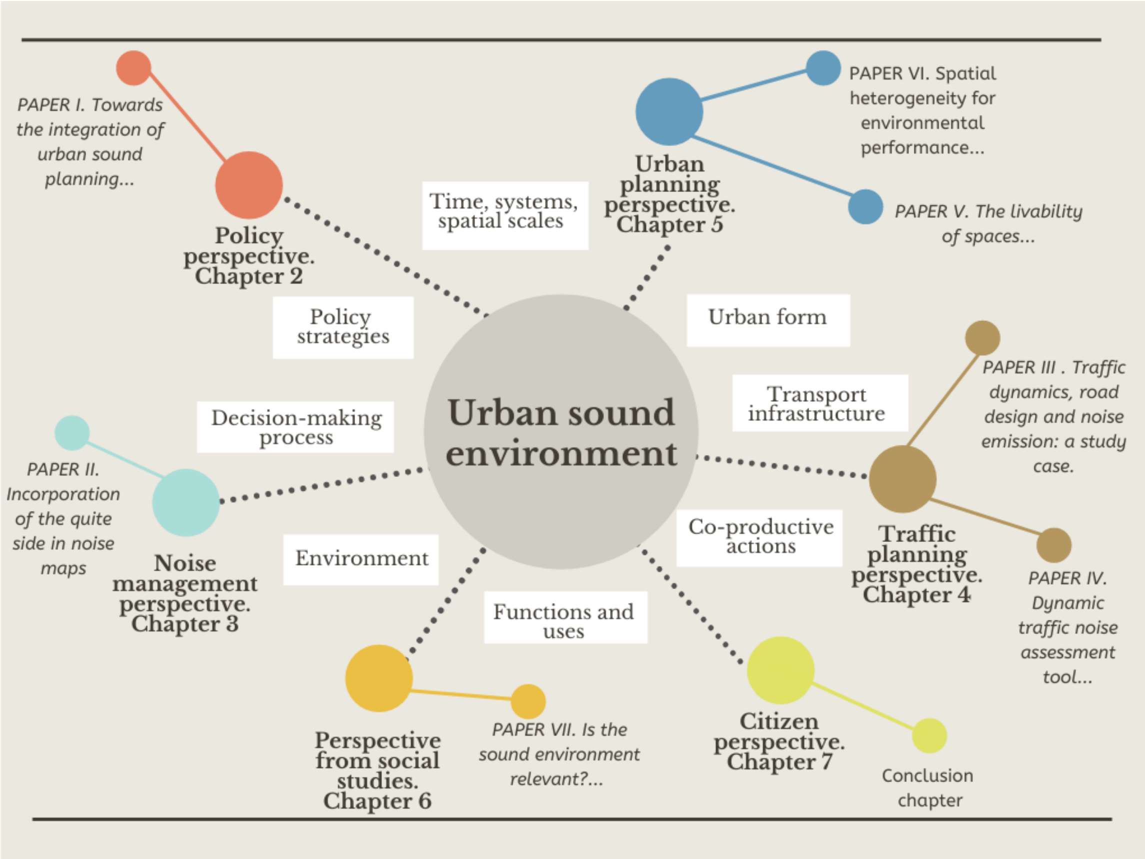

Figure 1.2: Urban sound environment: overview of the concepts and papers presented in the thesis.

More details about the different studies can be found in the following chapters and the appended Papers.

Chapter 2

Urban sound planning and its practical implementation

One of the main intentions of the EU Project SONORUS [1] was to understand, influence and improve the urban planning process mechanisms within an urban sound planning perspective. For this, the project carried out the study of four test sites. Each of them presented different approaches to include the concept of urban sound planning, responding mainly to the needs regarding the study and improvement of the sound environment and the urban scale. Paper I presents these test sites and the different approaches, tools and strategies carried out in each of them. The main interest for the present thesis is on the discussion about the inclusion of a holistic approach in urban sound planning and how it can promote liveable and sustainable cities (Chapters 3 and 4).

2.1 Introduction

During the 70s, the increasing concern for the environment led to the study of environmental services or ecosystem services, which contribute to the wellbeing of people, taking advantage of the contribution of natural capital through the interaction with human, social and built capital. However, the intention to reduce the negative environmental impact did not change much in terms of *how* to deal with it. Regarding noise reduction in Europe, the development of legislation has been decisive, especially with the appearance of the European Noise Directive (END) [41]. The intention

[1] The FP7–PEOPLE–ITN Marie-Curie Action, 'Initial Training Network' EU Project SONORUS, aimed to offer training to Early Stage Researchers (ESRs) in transdisciplinary research, focusing on urban sound planning. The training included real-life urban test sites that presented a poor acoustic environment.

within this framework is to 'avoid, prevent or reduce the harmful effects of noise on human health' from several noise sources, including road traffic. To achieve this, a common approach regarding the management of noise within Europe is needed, going beyond the regulation of noise level as a ceiling. Within this vision, we are committed to a holistic approach that encompasses the concept of acoustic environment from an urban sound planning perspective.

To test these approaches, actual planning problems that include urban sound planning are incorporated to the EU SONORUS project. Four test sites where chosen (Antwerp, Brighton & Hove, Gothenburg and Rome). In this context, the city partners are crucial for the implementation of this holistic approach: they provide the test cases, they are an important stakeholder, but they are also the ones that can really make the urban sound planning become a reality within the city halls.

The interest to incorporate this paper in the present thesis is due to its general vision of the problem statement, the variety of acoustic challenges that the European cities face, the openness in the analysis of strengths and weaknesses of the methodologies proposed and the results. All this is explained in sections 3. 'Discussion' and 4. 'Conclusions' from Paper I.

2.2 Brief comments about the test sites

The following lines explain briefly why these test sites were chosen and how we worked with them. All test sites have issues regarding noise regulations as the noise levels are higher than the limit for the expected uses.

- Antwerp Rivierenhof Park is subjected to high noise levels due to heavy traffic in the surroundings and a road that divides the park in two parts. Different solutions were tested to mitigate the problems cause by the presence of this road. Among them, the working group used vegetated surfaces and barriers to control the sound environment based on results from numerical Finite-Difference Time-Domain calculations. Combined measures were estimated to achieve up to 30 dBA reduction for pedestrians.

- In Brighton's problem at Valley Gardens was approached through the inclusion of more detailed noise maps, sound maps and soundscape maps that improved the analysis of the area. Valley Gardens is a vital long park that seeks to become a key area of the city as an attractive and safe space. Since traffic reduction was not possible, the strategy was to achieve auditory masking to reduce perceptual effects of traffic noise. For that, the working group tested different gravel materials to improve the sound environment by masking road traffic noise.

- Gothenburg's new development at the Frihamnen area had the intention to allocate 15000 new residences, which is a great challenge for the city. Several noise sources are present, road traffic being the dominating one. A whole new traffic layout is planned. Our approach was to study such traffic layouts and test different traffic scenarios as an anticipatory process through a dynamic traffic noise tool capable to estimate the noise coming from traffic at different places. Noise levels and noise events can be reduced by modifying the traffic layout according to the expected functions and uses. However, if measures are not taken, there is a huge risk that the area becomes even more noisy and unliveable than it is right now.

- Rome's test site was the Colosseum area. This site is submitted to high noise levels and it does not seem to be suitable for the enjoyment of visitors. The government wants to improve the attractiveness of the area and its preservation, including the sound environment. Questionnaires were prepared to analyse the visitors' perception of the area and recordings were performed. Results showed that visual attractiveness was high, however, sound quality was not. Recommendations were performed to the government, including periodic monitoring of the noise levels, improving the information about the existing routes for tourists and reducing traffic in the surroundings, among others.

2.3 SWOT Analysis as one of the main outcomes

One of the main reasons for carrying out this research was the several discussions that the SONORUS students had regarding the test sites and the interactions with the city offices. To develop a strategic planning at each of the test sites and see the global status, a SWOT Analysis was carried out for each of them.

- Strengths. (What do we do better?) The holistic urban sound planning concept shares the aim of urban planning development, which is to make spaces more liveable, resilient and efficient. Therefore, the approach through several disciplines is guaranteeing the holistic vision. Moreover, direct contact with the city council is largely valuable, while not always possible. Freedom to carry out the project as in the case of Gothenburg is seen as a strength and an opportunity, as no restrictions or impositions are present. Also, the implication of the visitors (a relevant stakeholder) at the early stage of the decision-making process is valued.

- Weaknesses. (What could we improve?) Most of the weaknesses could be resolved if the different stakeholders understand and incorporate the study of the urban sound environment at the beginning of the project (in its planning phase). Meanwhile, in the current study we detected several aspects to improve, e.g. the lack of contact with the city planning working group is seen as one of the main weaknesses: it might restrain the full potential of the concept of urban sound planning. In addition, each site has its own complexity: the urban scale and the timeframe, the various changes in urban proposals, the difficulties in accessing information on urban projects, the numerous laws coming from different entities, etc. All this ends up restricting both the process and the results.

- Opportunities. (What good opportunities can we spot?) The study of real cases allows to propose local/specific solutions that can improve the quality of life of citizens. With this approach, interventions prior to urban decisions in close contact with public authorities and relevant agents have an impact not only in the short term, but can also improve the resilience of the area in all aspects (monetary, environmental, social, etc.)
- Threats. (What obstacles do we face?) The main threat is that the working groups were not part of the decision-making process, and most of the recommendations were not considered in the final proposals, with the risk of increasing environmental acoustic degradation, leading to other collateral problems.

2.4 Where are we now regarding Urban Sound Planning?

The present study demonstrates that improved solutions that go beyond noise control management and legislation fulfilment are possible, and the concept of Urban Sound Planning is starting to be a reality; there is an increased development of tools capable to embrace this holistic approach, and a better understanding of the urban sound environment has been achieved. Since the project started, structured sessions named *Urban Sound Planning* at different international Congresses (e.g. Internoise, Euronoise, ICA) have taken place; these sessions are contributing to establish this new discipline, however, they are mainly targeting the acoustic community. We think that the main relevance of the urban sound planning approach is the capacity to attract architects, urban planners, final users and other relevant stakeholders (e.g. construction companies, city planning and traffic planning offices). Possible ways to improve this (apart from the ones mentioned in Sections 3 & 4 from Paper I) are to:

- Focus on responsive urban environments from the acoustic point of view, capable to interact with the urban systems and adapt to the users and the different situations. Find evidence through examples: have a deep understanding of them and be able to communicate the findings to politicians, urban agents and final users.

- Reconsider the role of the urban sound planner: a better understanding of how the design processes takes place in different professional fields (acoustics, urban planning, traffic planning, environmental concerns, user experience, etc.). Expand knowledge and interdisciplinary communication by exploring complementary skills.

- Bring the concept of Urban Sound Planning to relevant congresses in the field of urban planning; the SONORUS students have begun to make efforts presenting research findings at urban planning conferences (*AESOP, Beyond 2020*), publishing in scientific journals outside the field of acoustics (e.g. *Landscape & Urban Planning*), giving presentations and popular seminars to urban planning office employees, etc.

- Permeate different fields in academia that work with the city. Thus, other professionals will be aware of the importance of the sound environment for citizen welfare.

- Increase awareness about the sound environment among stakeholders of the planning process.

- Increase public awareness: provide information to citizens on the importance of the sound environment and of the opportunities for improvement.

As the urban environment is submitted to constant change, a responsive approach capable to understand and adapt to such changes is needed more than ever. Even though SONORUS was a limited timeframe project, it started to expand the urban sound environment approach. With it, we aim for a better understanding of relations and interdependencies between the urban form, the urban life and the sound environment.

Chapter 3

The relevance of restorative environments for urban development: the quiet side in noise mapping

Paper II arose from the importance of the study of noise restorative places such as the inner yards. These places constitute a powerful tool in the development of new urban areas, as the regulations consider them as part of the public/private, built/non-built space. In the increasing densification process, e.g. in cities like Gothenburg, this type of construction is relevant as it is largely used by the city developers. Accurate and efficient tools are demanded to properly predict the noise levels at these places. In the work behind Paper II, the *Qside implementation model* was developed and tested within real case studies.

3.1 Introduction

All around the world, the city densification argument is present in every aspect of the urban development (social, urban, economic, environmental, etc). Regarding the sound environment, the quiet area concept is gaining power, especially in the development of new urban areas. These areas are known as the ones not exposed to sound pressure levels above a certain magnitude [42]. However, legislation is usually based on limit values for the most exposed façade, where the European Noise Directive, known as END, aims to 'avoid, prevent or reduce the harmful effects of noise on human health' [41] from several noise sources, including road traffic. The trend now has been changed, as the possibility to accomplish reduced noise impacts at the most exposed façade becomes difficult and expensive [43]. In this context, the quiet area concept has been welcomed, specially from the annoyance and sleep disturbance perspective, as a powerful tool to reduce noise levels while achieving the desired densification (e.g. allowing the construction of new buildings, while fulfilling regulations).

The main tool to study the sound environment in agglomerations is through noise maps. To perform such calculations within the legislation, noise prediction software have been developed (e.g. CadnaA, SoundPLAN, Lima). The software incorporates different calculation methods, according to legislation, e.g. Nord2000, ISO 9613, NMPB–Routes, CNOSSOS-EU, Nordic Prediction Method. Following the legislation, the intention of the noise mapping techniques is to calculate noise levels at the most exposed façade, with the drawback of noise level underestimation at the inner yards [44]. The popularity of inner-yards increased as the concept of quiet areas and common restorative places was introduced. They have been identified as spaces with the capacity to moderate the adverse effects of road traffic noise [41]. They are one of the four principles in the WHO *Environmental Noise Guidelines for the European Region* document (Reduce exposure to noise, while conserving quiet areas; Promote interventions to reduce exposure to noise and improve health; Coordinate approaches to control noise sources and other environmental health risks; Inform and involve communities potentially affected by a change in noise exposure) [45].

Connected to this, the guideline value in Sweden regarding the outdoor level $L_{Aeq,24h}$ has been raised from 2015, which until then was 55 dB [46], up to 60 dB in the SFS 2017:359 regulation [47]. In the case there is access to an outdoor area that belongs to the house, 50 dB $L_{Aeq,24h}$ and 70 dBA maximum sound level shall be fulfilled there. However, it also allows building housing if levels are above those 60 dB. This regulation raised the $L_{Aeq,24h}$ level to 65 dB in the case of new small flats (up to 35 m^2). Regarding inner-yards, the regulation sustains that one can build housing with any noise level toward the street (e.g. 85 dB), as long as half of the dwelling-rooms (bedrooms, living rooms, etc.) are on a side with 55 dB. This is where the importance of accurate noise level calculations of such spaces becomes crucial.

3.2 Aim

The noise level calculation for the inner yards depends largely on the multiple façade reflections. Accurate models capable to calculate them have been developed, as the application of the finite-difference time-domain (FDTD) and the pseudo-spectral time-domain methods (PSTD) [48, 49]. The computation time has been a drawback for these methods. Having this in mind, an engineering model, known as *Qside model* was developed within a previous project [50]. The aim was to obtain reliable results to predict the noise levels at the shielded areas at a low computational cost, and that calculations can be incorporated into the current noise mapping techniques.

3.3 Remarks

The input for the model is mainly on geometrical parameters: the width of the canyon street, the height of buildings, the distance from source to the top edge of the building, etc. In order to achieve a closer connection with noise mapping software calculations, the present research extended and implemented the previously developed model.

The engineering Qside model is focused on the diffraction over the buildings considering reflections in both the inner yard and the street canyon. When the inner yard is totally shielded (i.e. without openings or other paths not being over the roof), the result of the *Qside implementation model* is dominating. When it is not, the reflection in the horizontal plane may be dominating. In the last case, the calculations can be performed through noise mapping software, as diffraction and reflections from the *side* of the building are included.

The paper presented within this topic (Paper II) 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, the development of geometrical parameters at complex situations, the effect of air absorption based on the ISO 9613-1 [51], as well as decorrelation due to randomness in the propagation domain. Scattering due to turbulence was incorporated based on [52]. The model also implemented the road traffic source model Nord2000 [53].

The *Qside model* only accounts for closed inner yards (Fig. 3.1). However, approximations to these types of spaces might be possible when the main noise contribution is shielded by a continuous building without gaps. This type of case is explained in the section below (Outcomes), resulting in a good agreement, with a 3 dB (L_{Aeq}) difference between the *Qside implementation* and the performed measurements.

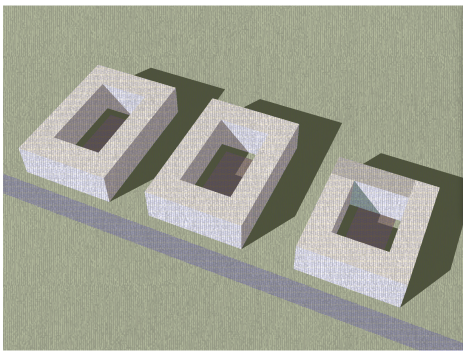

Figure 3.1: Example of closed courtyards.

3.4 *Qside implementation* improvements

The compared calculations between the *Qside implementation* and the noise mapping software are made for hard ground and both soft (20 % absorption) and hard façade (3 % absorption). During the implementation process, inaccuracies in the *Qside model* with the usage of soft façade were found and remarked as future work in Paper II. The inaccuracies correspond to errors in the *Qside model* when soft façade is studied. Later on, these errors were corrected and advised to the developers of the *Qside model* [54]. The inaccuracy was found in the attenuation within the canyon street ($A_{can,flat}$); an exponential factor resulted in an overestimation of the noise levels (replacement of ρ^2 to ρ^6, where ρ is the reflection factor of the façade) (see Fig. 3.2).

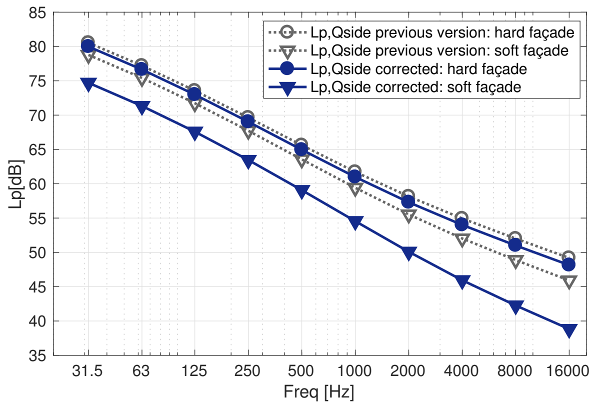

Figure 3.2: Contribution to the background level. Soft and hard façades: previous and corrected version. Line source with L_W=100 dB/m in each frequency band.

As previously mentioned, the *Qside implementation* calculations were compared with noise mapping prediction calculations using the *SoundPLAN* software with the Nord200 Road model. The higher the reflection order in the noise mapping software, the higher the agreement with the *Qside implementation*. A corrected comparison is shown in Fig. 3.3 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, as it is the legally prescribed approach, 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}).

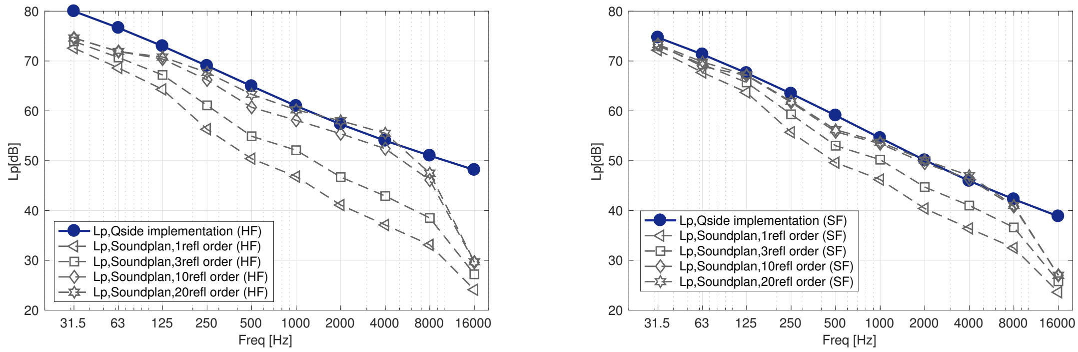

Figure 3.3: Contribution to the background level. Lw=100. Line source example. Calculations from the *Qside implementation model* and *SoundPLAN* with hard (left) and soft (right) façade

The large number of reflections that the noise mapping software calculations need to get a higher degree of accuracy, makes it computationally expensive to calculate noise levels in protected areas for entire cities through current techniques and methods, such as noise mapping software.

Fig. 3.3 reflects minor deviations 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. In this sense, the *Qside model* only accounts for the direct source-receiver ray to base the air absorption, resulting in a drop at high frequencies in the noise mapping software calculation, leading to inaccuracies in the *Qside model*. Regarding differences in the low frequencies, the diffraction model of *Qside* starts to fail; the deviation starts to get significant at 160 Hz and gets severe at frequencies below 50 Hz. In this regard, the *Qside* is based on the Harmonoise model, which overestimates the very low frequencies [55], and the calculations within *SoundPLAN* were performed with the Nord2000 model, which is more accurate in this respect.

3.5 Outcomes

A comparison with real measurements in a closed inner yard from the city of Gothenburg, Sweden is included in Paper I (see Fig. 7 and 8). The total difference between measurements and the *Qside implementation* is about 3 dBA, with very similar spectra. From the other side, 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, once Paper I was presented. In this case, 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 [56].

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. 3.4), and a series of geometry simplifications were applied in the model, simulating a closed inner yard. The noise level resulting from the measurement was 51.6 dB (L_{Aeq}). The *Qside implementation model* resulted in a noise level of 54.3 dB, making a difference of 2.7 dB (L_{Aeq}), which is considered as a good agreement in this context. The difference of about 3 dB may respond mainly to the geometry simplifications performed in the height and shape of the buildings.

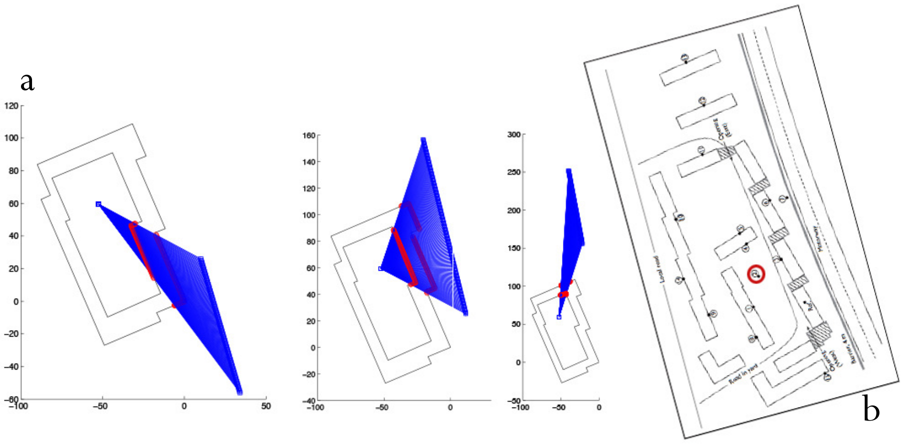

Figure 3.4: Snapshots on the *Qside implementation model* calculations (a) and the real scenario (b)

3.6 Limitations and future work

The implementation model has certain limitations, however, due to the good agreements found with Boundary Elements Method and analytical diffraction theory for simplified cases [57] (to validate diffraction and ground effect), and within the measurement comparisons, the proposed engineering model can be considered as a reliable tool to predict the noise level at shielded areas as a correction to the results 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 [58]. The idea is that the results from the *Qside implementation model* can be incorporated into the noise mapping prediction software. Advances have been made in developing a more generalised use of the *Qside implementation model* [59]. The direction is here to not only improve the model itself, but combine the study with that of air pollution, considering different morphologies and which ones could result in a better sound and air quality scenario. The first steps look towards the automation process we previously mentioned. Yet, one of the main limitations to study different urban morphologies is when small openings in buildings are present (tunnel) for otherwise shielded inner yards, where e.g. lateral (sideways) diffraction may become relevant, and wave based modelling [60] or an engineering correction formula based on measurements is needed.

Moreover, the *Qside implementation model* considers traffic as a constant flow and variations in time are not included. With this idea in mind, the following chapter (Chapter 4) compiles the investigation regarding the importance of traffic dynamics within the built environment.

Chapter 4

Transport strategies, traffic dynamics and noise emission

Papers III and IV 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.

Public areas, such as sidewalks, squares, parks, etc., especially the ones located close to the noise sources, may be very sensitive to the traffic dynamics, which we are addressing here. Therefore, 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. Previous reports have highlighted the importance of the way we represent and express the amount of noise, in understandable ways for everyone, such as 'events, duration and quality' [61]. Special attention in the present study is placed on developing forms of maps to better see the effects of proposed scenarios.

Both papers use as testbed the future development of the Frihamnen area, in Gothenburg, Sweden (Fig. 4.1). This area is about 1 km^2 large and the city's plan was to turn it into a dense-mixed urban area with 15000 inhabitants and the same number of working places (more information is available in [62]). The project is confronted with several challenges, especially regarding the environmental performance. In the case that concerns us the most, the majority of the selected area is submitted to noise levels above 65 dB (L_{den}), with road traffic as the main noise source.

Figure 4.1: The Frihamnen area and its comparison with the city centre. Picture from the right is one of many scenarios that the Planning Office of Gothenburg City had proposed.

Paper III focuses on the development of the tool with the Frihamnen area as a testbed for different plausible scenarios regarding traffic planning layout. With the intention of improving the tool and study its potential, Paper IV uses a small part of the scenario designed for Frihamnen, where an intersection is designed as a crossroad or as a roundabout.

4.1 Introduction

In contemporary cities, special attention is paid to accessibility as one of the driving forces that guarantees social, environmental and economic sustainability[1]. For the environment, improving mobility is seen as an urban opportunity; how people use and move in cities is approached as a way to improve habitability. Concern about increasing traffic flows in cities is intrinsically related to both traffic design and transport management. 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 exposure to noise is caused by traffic noise [66].

Several publications have highlighted the experimentation of sleep disturbance and nuisance due to noise events in transportation [67–69]. To study these adverse effects, discomfort has been addressed as one of the main indicators in recent decades. However, this is changing towards the study of direct health effects, since summarising them in the level of annoyance has not led to any significant action or result [70].

[1]Sustainability in this sense means to balance these three pillars seeking to improve quality of life, seeing them as a nested concept [63, 64], however, limited to the achievement of more efficiency [65]

4.1.1 The main way to study the sound environment nowadays

With noise as one of the biggest wastes due to road transport, efficient transport layouts are needed, as they can bring opportunities to improve the sound environment. In order to find a common assessment to control the sound environment in Europe, the EU legislation, known as the Environmental Noise Directive (END) [41], requires the implementation of Noise Action Plans as periodic plans to describe the actions that authorities must take to reduce or prevent noise. These plans are based on results obtained through strategic noise-mapping, according to the END. The commercial noise-mapping software techniques currently used consider traffic as a static flow, with an average speed and a constant traffic density. This type of study is mainly entitled to assess a macro and/or mesoscopic scale, giving as output the day-evening-night noise level. Several sources of evidence highlighted that this type of assessment may lead to underestimations in noise levels [71–73] and annoyance [74], whereas time patterns are strongly linked to the vehicle dynamics, playing an important role in transport behaviour and its noise emission, interfering, as previously mentioned, with outdoor and indoor human activity. With high traffic fluctuations and multiple 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 main intention is to analyse the time-averaged (equivalent) noise level at the most exposed façade. It seems that we are facing a lack of tools to study the sound environment as part of a larger picture, the urbanisation process.

4.2 Aim

Since vehicle dynamics and time-pattern fluctuations are concluded to be relevant for the sound environment, and therefore, for the suitability of evaluating the connection with human activities, this study develops and implements a model based on the individual-vehicle characteristics as function of time. To do this, real study cases within the Frihamnen area in the city of Gothenburg, Sweden are used. The use of real case scenarios makes the work more realistic, as there are several restrictions, such as traffic flow demands and space constraints. The main condition in developing these scenarios for both papers was that all traffic needed to be handled in a way that vehicles traveling from their starting point to their intended destination, should be entitled to do so at all times. The peak hour traffic flow was calculated, simulating the worst scenario within a year.

The intention is to continue developing solid bases to justify urban practices directly related to traffic planning and the impact on the outdoor sound environment.

We hope to help to find a broader agreement among decision-makers, demonstrating the need and the opportunity that comes with an anticipatory planning-process, capable of analysing the consequences of certain urban traffic decisions.

4.3 The tool

The tool attempts to study the sound environment through the analysis of road traffic noise emission calculated from individual vehicles as a function of time, reflecting a more realistic urban scenario. It is based on each vehicle's individual characteristics (speed, acceleration, driving behaviour, type). This model considers a flat city scenario with hard ground and focuses on the study of relatively small areas. In this way, the main features can be described in a simplified way. Future tools can be developed to be more general. The tool consists of two main parts (Fig. 4.2):

- Traffic simulation: the microscopic traffic simulation gives as output the position, speed and acceleration versus time of each vehicle, using the car-following traffic simulation software *Vissim*.
- Noise emission: the developed *Matlab* scripts take the results from the first part of the model and compute the source strength as function of time for each vehicle. For that, the CNOSSOS-EU noise emission model [75] is incorporated plus the Harmonoise acceleration model [76]. The tool includes as well sound propagation modelling based on a flat city configuration.

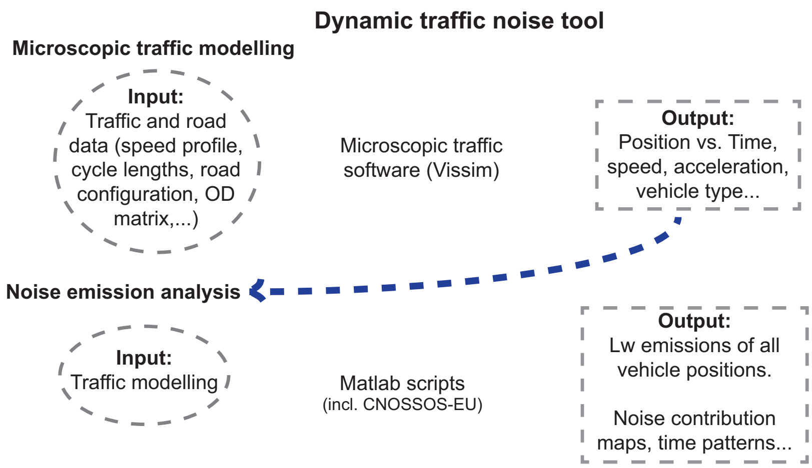

Figure 4.2: Model scheme.

One of the limitations already mentioned in the previous paper, is that the model lack air attenuation, however, we are aware of its relevance. For this purpose, a comparison between a commercial noise mapping software (SoundPLAN), the analytical CNOSSOS-EU modelling of air absorption and the developed tool was performed in Paper IV, through a simplified setting (straight road) and five study points selected (10, 50, 100, 200, 400 m distance from the centre of the source line). Further details can be found in Paper IV. Fig. 4.3 shows that differences regarding the inclusion of air attenuation in the analytical model varied in the range 0.9–2.5 dBA at larger distances (100 m or more). Similar differences (0.9–2.8 dBA) were found between the noise mapping software, which includes air attenuation, and the dynamic traffic noise tool, which lacks it. The results showed that the model is reliable up to a distance of 100 m. from the source, accepting a difference of 1 dB (L_{Aeq}). Distances further than 100 m are not so relevant in typical urban areas, as buildings will already affect the sound propagation.

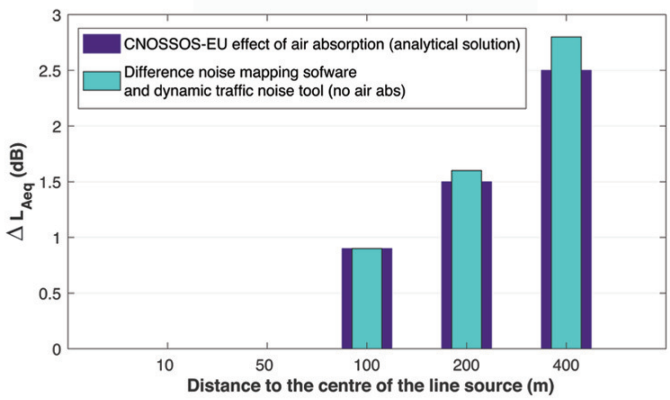

Figure 4.3: The effect of air absorption. Results from the analytical model, and the differences between the noise mapping software and the dynamic traffic noise tool.

The present tool includes heavy, medium-heavy and light vehicles, as well as combustion engines and pure electric vehicles. However, measured data do not follow the CNOSSOS-EU road traffic source model premise: all vehicles driving at the same speed have the same source strength. Within the developed tool, a randomisation of the variability in the emission among the same vehicle type is introduced in the study presented in Paper IV. Variation in source strength due to acceleration is modelled according to the Harmonoise source model [76].

The tool has had a long development of a technological process (problem description, finding information, gathering ideas, identifying needs, work planning and design, limitations, testings and evaluations). An example of the work carried out is presented in the following figure (Fig. 4.4) as a work in progress image.

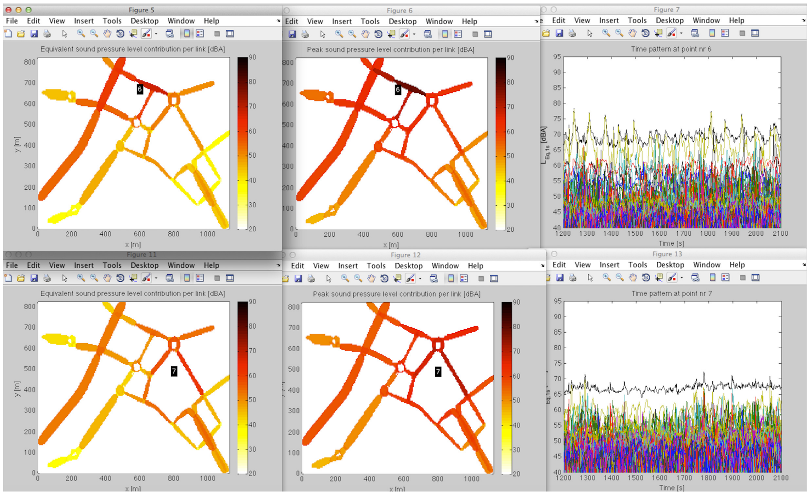

Figure 4.4: Development of the tool: First plots of contribution maps and time patterns.

4.4 Remarks: a few ways to represent the information and outcomes

Several tools similar to the present one has been developed and continue their development (see the 'Introduction' section in Paper IV). What we find more relevant about this type of methodology based on time-pattern analysis, is the capacity to introduce indicators that can reflect the urban traffic noise dynamics: statistical indicators, calm periods and noise events, presented as visual outcomes (e.g. difference and contribution maps) that may be useful for the relevant stakeholders.

One of the main concerns in the present study is how to communicate the indicators within the scope of urban sound planning, and, through its representation, try to attract the different agents involved in the urban planning process. In the following pages, a series of figures are included as a demonstration. The full description of these studies can be found in Papers III and IV. The Frihamnen area (Paper III) is studied through eleven analysis points capable to represent the different situations that can be found in the area: high traffic flow in the surroundings, closeness to piers, between two roads, intersections, etc. Nine scenarios were developed with the condition of holding the same traffic capacity: 1) Base scenario from the Traffic Office of Gothenburg City with adaptations; 2) Remove parallel road to highway; 3) Remove roads close to piers; 4) Transform intersection with lights into a roundabout; 5) Reduce speed on highway to 50 km/h; 6) Reduce speed on bridge to 50 km/h; 7) Reduce speed on the road close to the piers to 30 km/h; 8) Remove medium-heavy and heavy vehicles; 9) Acceleration set to 0.

4.4.1 Contribution maps

Noise pattern over time is poorly reflected by common descriptors as L_{den} and L_{night} since they are energy-averages over several hours. The temporal pattern fluctuation is considered to be of interest regarding acoustic comfort and human health, especially when studying sleep disturbance ([67, 68, 77], among others). The maps in Fig. 4.5 show the equivalent sound pressure level over 900 seconds $L_{Aeq,900s}$ and the peak level, L_{Apeak}, which each of the road segments contribute to a certain study point: using the equivalent sound pressure level and the peak level. The contribution map calculations need to be further developed, however, we are interested in the way the information is presented and this type of maps might help the diverse urban agents' assessments, as they can rapidly see where the 'problem' or 'opportunity' is coming from depending on the interest.

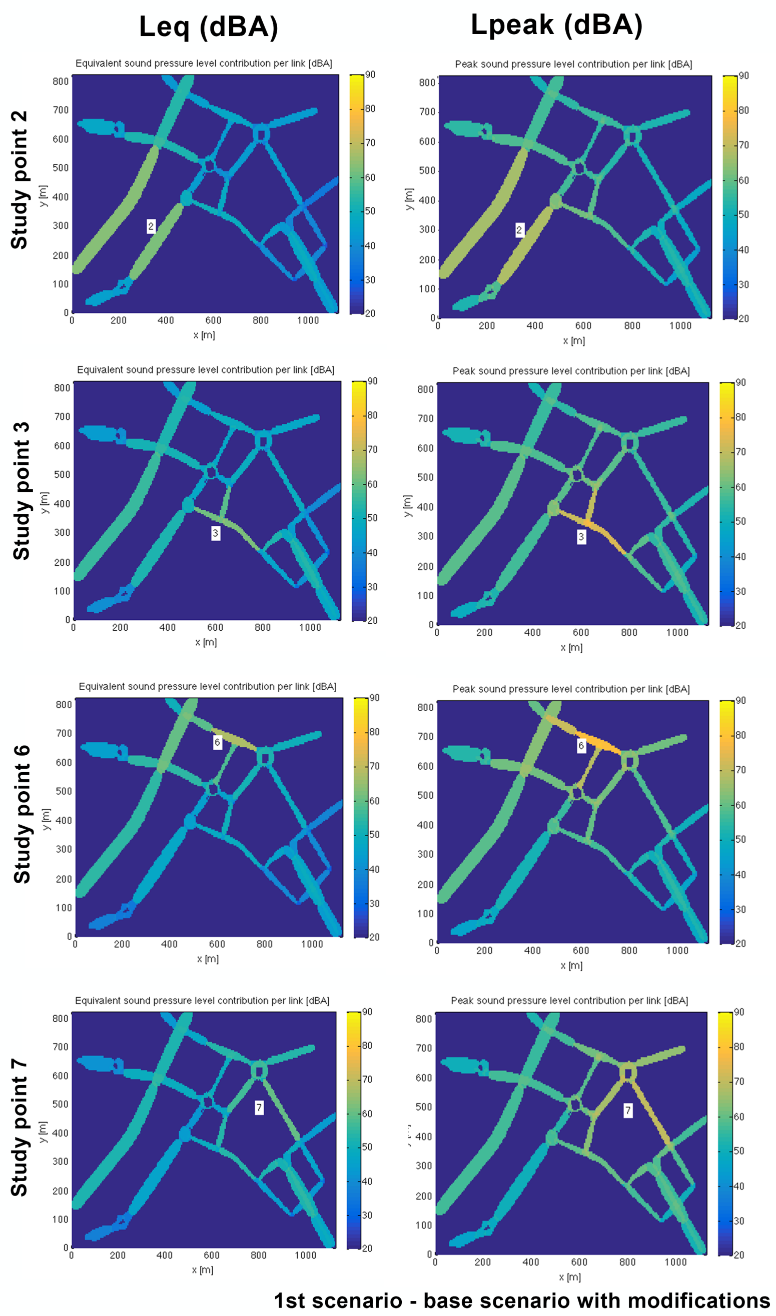

Figure 4.5: Frihamnen link contribution maps to study points: equivalent sound pressure level link contribution (left) and peak sound pressure level link contribution (right), both in dBA.

4.4.2 Noise events and sound pressure level

The 1-hour equivalent level, $L_{Aeq,1h}$, is represented at each of the scenarios at all study points in Fig. 4.6. Removing roads close to piers (scenario 3) seems like a good solution for certain points, and similarly for a speed reduction on the highway (scenario 5). The scenario 8 that keeps only light vehicles, reduces levels up to 2.5 dBA. Urban decisions can be improved by such analysis; however, they need to be made in accordance with the functions and uses of the area.

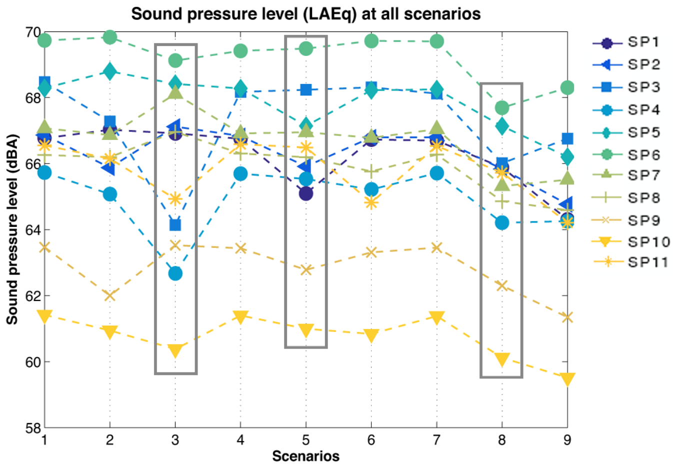

Figure 4.6: $L_{Aeq,1h}$ of all scenarios.

The number of noisy events is seen as a relevant indicator. However, the definition of event should be revised, and further studies are needed. For the present study, an event is qualified (based on [78]) as when the chosen noise level threshold is exceeded, lasting for at least 3 s and finished when the level has decreased 3 dBA below the threshold. We believe that the present indicator should be studied accompanied by others, and the controversy is served: What is the correct combination of indicators to assess the built sound environment and its relevance to the public? For example, within the same layout (base scenario) removing acceleration reduces 60 % of the events exceeding L_{10} (L_{10} is the noise level exceeded 10% of the duration, giving an orientation of the upper noise limit), while banning heavy vehicles reduces 7 %. However, the equivalent sound pressure levels resulting from the banning of heavy vehicles decreases by 2-3 dBA, at the same time as removing acceleration reduces the level by 1.9 dBA. These numbers represent an average among the eleven study points show in Fig. 4.7.

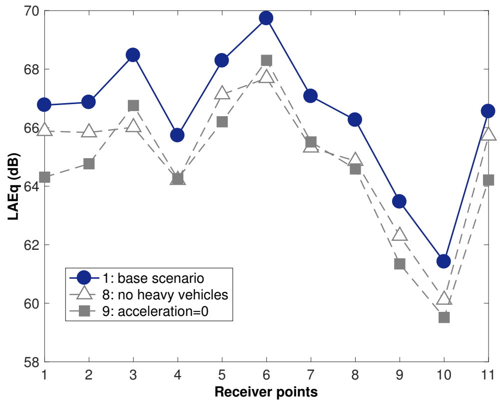

Figure 4.7: Frihamnen area: base scenario, removing heavy vehicles and scenario without vehicle acceleration.

4.4.3 Sound pressure level dynamic maps

Paper IV was born with the intention to deeply explore and improve the tool, through a simplified but realistic model: an intersection as one of the most relevant elements of traffic design. The study deals with a signalised crossing and its substitution by a roundabout. The following lines present a series of relevant outcomes. To graphically see the global effect on the sound pressure level of the different vehicle types, Fig. 4.8 represents the equivalent sound pressure level during peak hour, including light, medium-heavy and heavy vehicles for the first 15 minutes of simulation (a, b) and for the second quarter of hour (c, d). Consequences to the sound environment from vehicle dynamics are already visible within this peak hour: in the second quarter of hour there is already a visible road congestion on the incoming lanes at the roundabout (c) and high noise levels in the southern access lanes of the crossing (d). Martin-Gasulla et al. [79] already mentioned this issue, were unbalanced flows at roundabouts can cause a large amount of problems regarding delays and travel times, visible in the equivalent sound pressure level maps. The same time period is represented for scenarios with combustion engine (g, h) and electric (i, j) light vehicles. Differences are clearly appreciated. Moreover, a traffic flow reduction of 25 % from the base scenarios is added (e, f) with clear improvements regarding the sound levels at the majority of the area. Comparing panels (g, h) with (c, d), i.e. removing heavy vehicles, shows that the equivalent sound pressure levels at the whole area of analysis are reduced, and the traffic stream is smother on all roads. By substituting internal combustion engine vehicles (g, h) by all-electric ones (i, j), a clear noise reduction is predicted, where at distances of about 40 m or more from the roundabout (i), the levels are below 55 dB (L_{Aeq}).

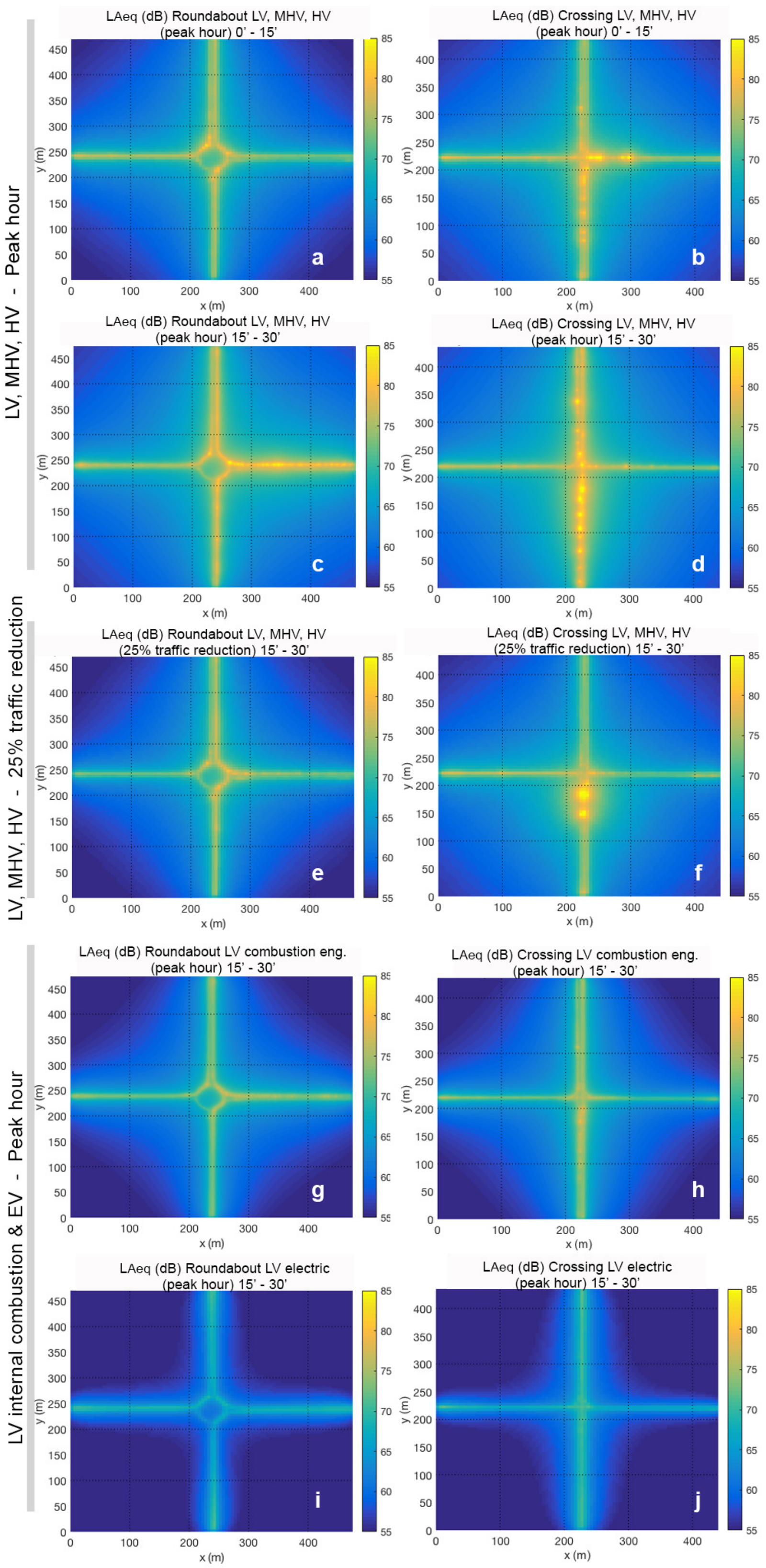

Figure 4.8: Equivalent sound pressure (dBA) for roundabout (left) and signalised crossing (right).

In general, reducing traffic by 25 % gives better results for the roundabout situation than for the signalised crossing one at all cases.

4.4.4 Other indicators: Centre of Mass Time (CMT)

We still do not know where the limit is of communicating average levels to the public and when do we need peak noise levels, single events patterns, etc. Several discussions are taking place in this regard, and both options are kept here.

As we previously pointed out, the study of nuisance seems to be not fully effective to improve the sound environment and the urban planning practices [70]. However, we believe that through the study of noise comfort, including the link to health aspects, we can find out several answers to the problem regarding the urban sound planning. In this regard, the number of events seems to be relevant, as longer quiet periods might have the capacity to mitigate/reduce noise annoyance [80,81]. A novel indicator, named Centre of Mass Time (CMT) has been introduced; the intention is to weight the cluster of quiet periods. The idea is that when the noise level is lower than the limiting one (e.g. 45 dBA), that time period gets a certain weight that increases linearly with the length of it. Thereby, the indicator is rewarding having few larger quiet periods than many short ones.

The CMT indicator is already explored in Paper III, through the comparison of different urban scenarios. It seems clearer to introduce this indicator with this type of study than with more concrete situations as the ones in Paper IV. For example, for the study of the whole area, study point 1, close to a busy highway, shows differences regarding the CMT indicator, with the limit value being the median level L_{50} (Fig. 4.9). Values go from +7 to -4 seconds relative to the base scenario (33 s), meaning that in case of scenario 5 (+7 s), where the speed on the highway is reduced, longer quiet periods appear. Contrary, scenario 8 (-4 s), with only light vehicles present, makes the quiet periods shorter.

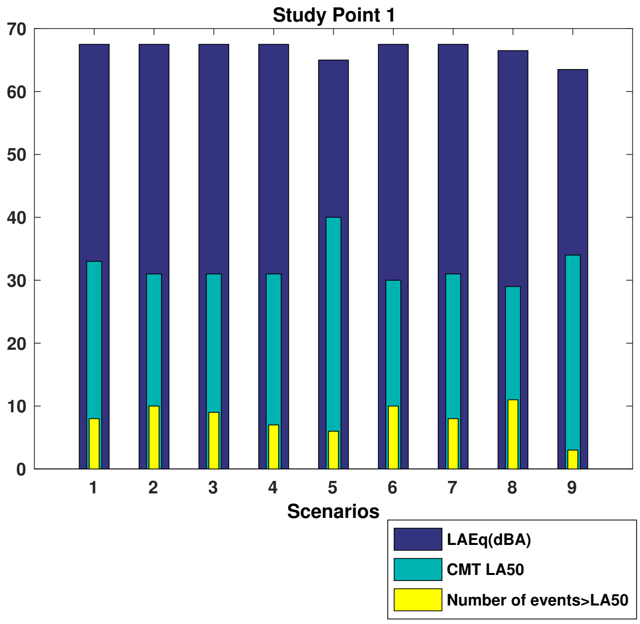

Figure 4.9: L_{Aeq}, clustering of calm periods (CMT) and noise events.

The CMT indicator is studied as well in the cases of Paper IV. The intention is to see 'how much accumulated quiet time do we have below the peak noise level, and how close to each other the peaks are in time' (CMT below L_{10}). At all study points, there is a negative correlation (r^2 from -0.66 to -0.92) for the majority of scenarios between the number of events NE above L_{10} and CMT L_{10}. This means that when the number of events increases, fewer silent seconds are clustered. This happens at all scenarios, except for scenario 1 (with all vehicle types having combustion engines) in the roundabout, where the unbalanced traffic situation reflects a more complex and unexpected behaviour. Another interesting aspect that the CMT indicator reflects is the presence/absence of heavy vehicles. Higher values of CMT L_{10} are present when heavy vehicle categories are included, especially for the crossing intersection. When this type of vehicles is removed, both intersection types have around the same value of cluster of quiet periods. Even though the equivalent noise level is higher, the presence of heavy vehicles in the present cases apparently reduces the rapid time pattern fluctuations (larger congestions, heavy vehicles damping the flow, less changes in speed, etc). The previous is interesting regarding what is pursued by urban planners and desired by the citizens at each built environment. We are aware of the possibilities that the CMT indicator might have and also its limitations. In this sense, a recent subsequent study to the publication of this article has proven its future usefulness and relevance [82].

4.4.5 Difference maps

Paper IV studies and improves the method developed in Paper III, as mentioned, and seeks to deepen its capacity to communicate aspects of road traffic, the approach to urban sound planning and its impact on people. With the intention to see the possibilities of communicating information, the following type of maps were developed in Paper IV.

The difference maps, in this case, the difference in equivalent level, L_{Aeq}, between the two intersections is showed in Fig. 4.10. These differences can be displayed as well for other statistical noise levels, e.g. L_{10} and L_{90}. They can be a useful visual outlet to study variations in the sound environment as a result of different urban decisions that will accompany a new urban area. In the present figure, one can easily see where the crossing intersection is having a better behaviour (lower values of L_{Aeq}), versus the roundabout. Rapidly, impairment due to traffic congestions are evident and possibilities for traffic planning improvements become extremely relevant.

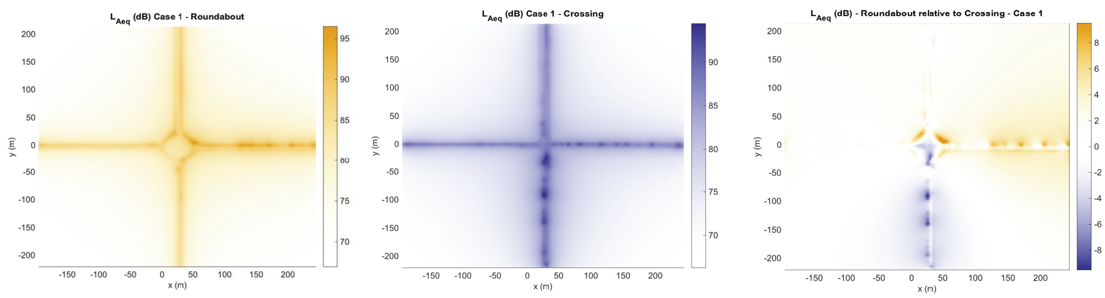

Figure 4.10: Equivalent sound pressure (dBA) for roundabout (left), signalised crossing (centre) and difference map (right).

4.4.6 Other outcomes

Other interesting results are briefly summarised in the following lines.

Acceleration was removed when testing source strength. Small effect (around 1 dBA reduction) was appreciated for the overall distribution of the sound power level at the peak hour. Since deceleration causes already a reduction in the source strength, the acceleration is partially cancelled by this effect. This effect should be further studied to understand how it might affect human perception. It is especially relevant for crossing intersections with traffic lights.

The substitution of combustion engine light vehicles by electric ones gave a mean reduction of the output source strength of approximately 4.5 dBA for both types of crossing.

For comparison purposes, commercial noise mapping software was tested with the same scenarios when traffic was reduced by 25%. A reduction of approximately 1.25 dB (L_{Aeq}) at the selected study points was found from both the commercial noise mapping software and the developed tool (scenario with combustion engine light vehicles). An extra bonus in L_{Aeq} reduction appears when heavy vehicles are included in the study of the 25% traffic reduction, with an average reduction of 2.7 dB (L_{Aeq}) at the roundabout study points, and an average reduction of 1.8 dB (L_{Aeq}) at the signalised crossing.

4.4.7 Future work and possibilities of the tool

With the tools presented here, we attempt to explore ways to improve and develop the current urban practice in cities. We seek to find new approaches and/or improve current ones with respect to what is relevant for exploring the suitability of the sound environment for the development of human activities, in this case specifically studying the impact of the transport system on noise emission.

Further work regarding tool improvement is needed, e.g. incorporating air attenuation and the further development of relevant indicators. Improved accuracy on the data variability of the output power level might update the model to current and future scenarios. Moreover, the outcomes of the tool may be used for auralisation purposes, with the intention to evaluate and predict road traffic noise and human perception. The tool may also help studying different spatial solutions as a respond to programmatic demands. In this context, the relation between built and non-built space is of great relevance for the urban environment. The *Space Matrix* method [83] studies this relationship 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). They measure spaciousness and boundaries, suggesting certain relations with other city dynamics, such as the sound quality. Combining these density variables with physical characteristics 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 developed tool, the prediction of the vehicles' source strength as an estimation of the sound power level per unit area can be included as a variable for studying the quality of the sound environment.

Chapter 5

Urban form and the environmental performance

New Urbanism principles embrace the diversity and mixed-use as a guide to renew especially post-industrial areas, counteracting the concept of urbanisation by specialisation. Does this way of conceiving the city increase performance? Do we lose adaptability? Should we diversify or be redundant? Does this have an impact on the environment, on the sound environment?

Papers V and VI 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 transdisciplinary view. A continuous reflection on the study of cities where several fields of knowledge converge under the umbrella of *urban systems* was carried out. Students settle in different teams, responding to a common interest in the study of urban systems; along with three other members of the school, we investigated the interactions between socio-ecological and socio-technical subsystems and their ability to enhance or block urban processes. Spatial heterogeneity as a fundamental aspect of urban form is being investigated as a key strategy to increase the liveability of cities, to enhance or hinder performance and endurance of critical urban subsystems, such as transport and energy. It has several consequences regarding environmental quality (air quality and noise) and, therefore,

[1]IDEA League is a strategic alliance between European technology universities with the intention of cooperating in educational and research activities. The group is formed by Delft University of Technology (Netherlands), Chalmers University of Technology (Sweden) ETH Zürich (Switzerland), RWTH Aachen University (Germany) and the recent incorporation of University Politecnico di Milano (Italy).

on the welfare of citizens.

The work within the school resulted in two articles: Paper V and Paper VI. The first published paper within this work (Paper V) reflects on the complexities in the built environment and the consequences that the fragmentation of urban processes can have on the capacity of the city to adapt and avoid becoming an obsolete entity. At this point, the spatial heterogeneity has been addressed as a positive property of resilient urban environments. The second published paper (Paper VI) deals with the practical implementation of this framework, where new paths of urban development focus on diversification and improving performance. A real case of urban transformation, located in an industrial area in the city of Zug, Switzerland is studied. In search of sustainable development, Switzerland has focused its efforts on developing potential models that serve as an example, starting with the reduction in energy consumption and emissions per person per year, known as *2000-Watt/1-ton* CO^2. To study the possibilities of the area, a series of workshops were held at ETH Zurich, including researchers from different areas such as engineering, sociology, architecture, psychology, as well as representatives from the industrial area, the Siemens company in this case. The study analysed the development of prototypical patterns of sustainable development, focusing on four possible future scenarios capable of responding to environmental challenges. The scenarios contain variations in terms of construction types, mixed uses, mobility modes and target groups. The case studies investigate whether there are opportunities or inconveniences to transform an industrial zone into a fundamental part of the urban fabric of the city [84]. In the present investigation (Paper VI), we try to go one step further through an approach capable of identifying relationships between the key performance indicators (KPI) of air and acoustic quality. These indicators are mainly a result of energy and transport systems and spatial heterogeneity. Existing integrated methodologies on urban and environmental studies are applied.

5.1 Introduction

The rapid changes in social, economic, urban and climatic conditions have increased the pressure to find better ways to build sustainable and resilient urban environments. An efficient management of the city is sought, guaranteeing a certain adaptive behaviour. In this regard, urban environmental quality, including its acoustic quality, is conditioned largely on its comprehensive understanding from a multidisciplinary view. In this way, decision making could reduce costs, anticipating the complexity that the adaptation of these systems demands (see Fig. 5.1).

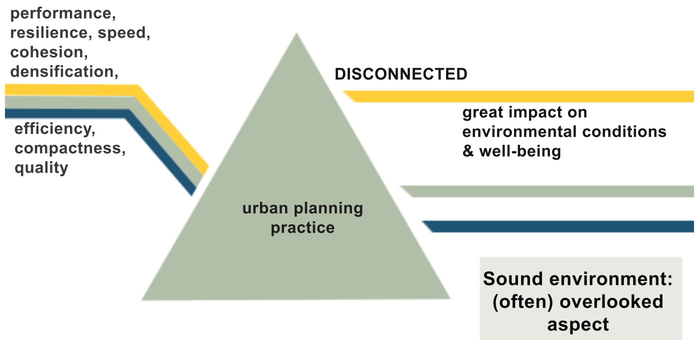

Figure 5.1: Urban planning practice input/output.

Under this vision of complexity, spatial heterogeneity is seen as an opportunity to allow the diffusion of risks, making our cities more adaptable to the unpredictable changes that may occur, while developing a suitable environment. However, it can compromise the performance of systems such as transportation, water, etc., Paper V introduces these concepts and sets a brief dialogue on the city as a system of organised complexity. In this organised complexity, systems must be flexible and adaptable to change, be resilient, otherwise they are vulnerable to threats. Resilience is, in principle, opposed to increased performance. However, given that the environment in which we live is limited, sustainable development means more than just reducing the use of inputs, and the resilience (at the end) looks towards improving the overall performance of the system [65] within a long-term perspective in a co-evolution process. At this juncture, the interest lies in how spatial heterogeneity affects the performance of urban systems, and its resilience, and, consequently, improves liveability of spaces, avoiding damaging the quality of life of people. Finding the appropriate balance demands a holistic thinking through the study of influencing variables and thresholds.

Providing anticipation mechanisms that avoid crossing those thresholds is pursued in a resilience thinking approach. Setting those thresholds is crucial, however, not easy: connections between underlying systems gives a real complex scenario, usually solved in a trial-and-error learning process [85], which may then be combined with a consensus at the political level (i.e. legislation).

Two of the main systems that degrade the environment are the transport and the energy systems. In this regard, mobility patterns and traffic design impact directly on the acoustic environment, diminishing the liveability capacity and the resilience behaviour. Transportation is seen as the main agent that decreases environmental quality in cities, where the main contributor to environmental noise in urban areas is road traffic [66]. In Switzerland, the traffic noise generates costs of about 1.5 billion CHF per year, representing direct damage to health and other negative impacts, e.g.

property value [86].

Urban strategies such as zoning may seem easier for control in the short term, since the activities and functions performed are the same, as well as the noise level targets. However, in the long term it can generate collateral problems such as an increase in transport, which leads to high levels of noise in a larger area, decreasing the quality of life.

Paper VI makes use of these concepts and this approach, using a case study. The aim is to study the role of spatial heterogeneity in the environmental performance and resilience of a future urban area. In this case within an urban area under transformation. The following sections explain further the work carried out. In both papers, the author of the present thesis worked with aspects about theory argumentation, urban variables and evaluation of noise pollution (performance and resilience indicators).

5.2 Some notes on the method

The study realised by Fonseca et al. [84] is expanded in Paper VI in order to evaluate the effects of spatial heterogeneity on the environmental performance of energy (in terms of greenhouse gas emissions, CO_2) and transportation (in terms of noise pollution) systems and their resilience capacity (reserve and potential margins). The study focuses on the performance of future urban scenarios for an industrial neighbourhood located in Zug, Switzerland (see Fig. 5.2). The current scenario has been targeted as a highly polluted 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), where high-rise buildings in the service sector set aside the industry; Campus (CAMP), with a university campus area, housing, catering areas, keeping part of the industrial production in place; Urban Condenser (UC), balancing residential, industrial and commercial uses with small local businesses.

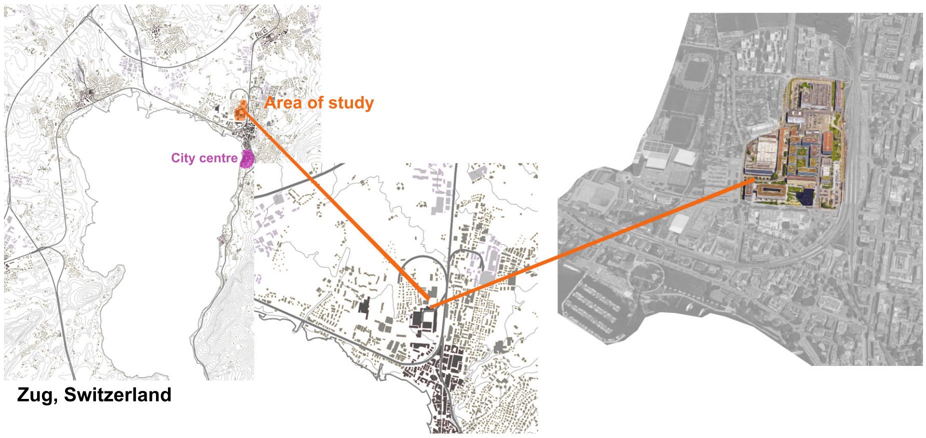

Figure 5.2: Area of study located in Zug, Switzerland.

The main data collected from the project [84] were the urban configuration, the number of inhabitants (families and students), workers and visitors in each scenario. Traffic and rail data (number and type of vehicles and railways per hour) were collected from documents of the Swiss Federal Office for the Environment [87, 88]. To calculate the forecast of road traffic data, the proportion of people in each of the scenarios traveling by private car and the number of trips per day (residents, students and employees) were counted based on the project data previously mentioned [84].

In addition, data on the number of inhabitants and workers per building have been included. For the purpose of the study, an estimate of both the location of the floors and their sizes was necessary. For this, the geometry and building typology, the location of the entrances and the type and number of occupants were taken into account. The data was included in GIS modelling and subsequently exported to the software *SoundPLAN* to perform noise calculations. The target values were obtained from the Swiss Noise Abatement Ordinance [89].

5.2.1 Acoustic indicators to study the scenarios

To analyse the environmental performance, a series of acoustic indicators were studied (see Table 5.1). The reason why these indicators were chosen is due to their representativeness to study the sound environment and its intrinsic links with the urban configuration, e.g. area exposed to noise, people exposure and quiet areas.

Indicators: noise pollution evaluation		
Id	Description	Measuring
ONE_{Ld}	Outdoor area exposed to noise during the day ($L_d > 60$ dB)	m^2
ONE_{Ln}	Outdoor area exposed to noise during the night ($L_n > 50$ dB)	m^2
QA_{Ld}	Quiet public areas during the day ($L_d < 45$ dB)	m^2
EO_{Ld}	Outdoor users exposed to noise during the day ($L_d > 60$ dB)	people (all)
EO_{Ln}	Outdoor users exposed to noise during the night ($L_d > 50$ dB)	people (all)
IE_{Ld}	People exposed to high noise levels during day (indoors) ($L_d > 60$ dB)	people (all)
RHA_{Ldn}	Residents highly annoyed by noise ($L_{dn} > 45$ dB)	people (residents)

Table 5.1: Indicators to evaluate noise pollution. All results given in percentage.

Moreover, the total number of residents for 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 5.3).

5.2.2 Acoustic indicators to study the resilience behaviour of the scenarios

Environmental attributes can be included as location attributes, whereas for example, accessibility can both increase and reduce the property value of a house [90]. The social costs in Europe, related to premature death or morbidity, of road and railway traffic noise exposure was estimated in 2011 to 40 billion €/year [91].

To assess the resilience behaviour, three indicators are used to study the absorptive capacity of the transport system, measured through the economic impact of noise pollution. A reduction in the number of people exposed to high noise levels will result in social costs reduction, giving a more robust and adaptive economic system. The indicators chosen were (see Table 5.2): 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 land-use restriction margin ($PM_{\mathrm{T,L}}$), where a 5 dBA decrease in the target noise level is pursued. This is already considered in the 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 ($L_{dn} < 55$ dB)	people (residents)
$RM_{\mathrm{T,P}}$	Reserve margin of housing depreciation to the total building stock value ($L_{dn} < 55$ dB)	number of houses
$RM_{\mathrm{T,L}}$	Reserve margin of total costs due to noise-induced land use restrictions ($L_{dn} < 60$ dB)	m^2
$PM_{\mathrm{T,L}}$	Potential margin of total costs due to noise-induced land use restrictions ($L_{dn} < 55$ dB)	m^2

Table 5.2: Indicators to evaluate resilience (economic impact of noise pollution). All results given in percentage.

Of Europeans, 25 % are exposed to noise levels above the limit values [66]. In Switzerland, road traffic is responsible for over 80 % of noise-related costs [86]. The

$RM_{\mathrm{T,C}}$ represents the external costs due to residents exposure to road traffic noise ($L_{dn} \geq 55$ dB). The external cost per dB is set to 128€/inhabitant, per year [92]. The above variables are computed according to the noise exposure level between 55 and 75 dB in 5 dB steps. The results are considered as the current noise cost of each scenario. To assess the target value, 75 % of the current noise cost was selected as the amount of money that can be spent as a consequence of noise costs. This was chosen with the idea of having a plausible saved margin. We are aware that this target value could be defined in a better way, however, the intention of the study is to propose a methodology to assess these costs and study the resilience behaviour of each scenario.

$RM_{\mathrm{T,P}}$ estimates the depreciation of housing value over the total value of the scenario. A target of 100 % is established, as zero depreciation is pursued. This value is not based on any previous research; however, it is derived from the concept of prohibition on obtaining residential building permits when access to a quiet façade is not granted. The total number of houses affected by noise levels above the limit is calculated ($L_{dn} > 55$ dB in ranges of 5 dB) in each scenario. We assume that each house accepts a level of 55 dB, calculating a total tolerance per scenario. The total residential price loss is calculated, based on a 0.5 % value loss per dB above the limit [93]. The sum of all these costs is subtracted from the total scenario tolerance, representing the total depreciation of building stock value.

$RM_{\mathrm{T,L}}$ is associating the social costs due to noise-induced land use restrictions. It includes areas with urban development possibilities, excluding small plots, roads, sidewalks, etc.

5.3 Outcomes and selected results

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

Paper V reflects on the tensions between urban performance and resilience, and the implications it can have on urban environmental quality. These implications are analysed through the effects of the interaction between the study of spatial heterogeneity (as a key strategy for urban resilience) and the transport and the energy subsystems on the human habitat and the liveability, attending to the main environmental stressors such as air and noise pollution. The discussion highlights the need for negotiation, trade-offs and coordinated strategies between the systems that conform the urban space.

5.3.1 Differences in outcomes due to the way data is studied

As an example of the outcomes of the study (Paper VI), people's exposure to noise and its relation to the selected diversity indicators are 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 VI, data are accounted in proportion). Similar proportions of residents exposed to noise are found among the scenarios (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 an increase in spatial heterogeneity is possible without increasing the proportion of people exposed to noise. However, since the population is varying between scenarios, the total number of residents exposed to noise is sensitive to those changes, e.g. the number of residents' indoor exposure (L_{d}) at the BAU scenario is 117, or 16 % of the total residents. At the UC scenario, this number is 254, representing 15 % of the total residents in the area (see Table 5.3).

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 5.3: Number of residents and users per scenario and number of people exposed to noise.

Regarding the number of residents exposed to noise, several diversity indicators show a strong positive correlation ($R^2 > 0.75$), such as the diversity of users (D_{U}), the diversity of land use (D_{LU}), and the diversity of target groups (D_{TG}), pointing out that higher levels in certain diversity indicators imply greater noise exposure to residents.

To illustrate the results of this work, Fig. 5.3, represents graphically the results of the interaction between the diversity indicators, in this case the diversity land use indicator (D_{LU}), and the sound environment ones. The D_{LU} score ranged from 0, without a mixture of land uses, and only one single land use present, up to 1, where all land uses are present. To have a balanced distribution of all cases, a value of 0.5 is sought, where half of the land uses would be present. There is room for improvement with respect to labelling, however, the purpose was not to define in a precise way these behaviours, but to map and distinguish them in terms of their performance.

For example, a scenario with a small proportion of people exposed to noise indoors during the day (EI_{Ld}) and a high value of land use diversity (D_{LU}) responds to a diverse and *green* scenario.

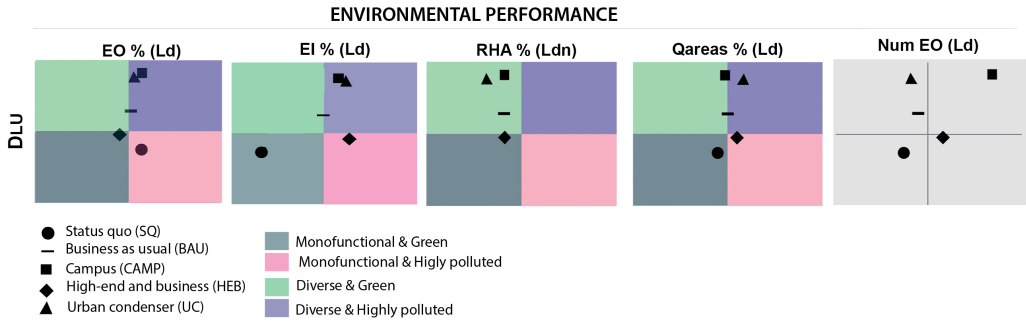

Figure 5.3: Environmental indicators (sound environment on the x-axis) and diversity of land use (D_{LU} on the y-axis).

Concerning the presence of quiet areas ($Qareas\%_{\mathrm{Ld}}$), all scenarios hold similar percentage values, despite D_{LU} differences. In the case of indoor noise exposure ($EI\%_{\mathrm{Ld}}$), similar percentages of people exposed to noise ended up in different values for D_{LU}. The HEB scenario represents a mono-functional and highly polluted scenario, while UC and CAMP are among the diverse ones, however, highly polluted scenarios as well. Studying the percentage of residents highly annoyed due to noise exposure ($RHA\%_{\mathrm{Ldn}}$), CAMP, UC and BAU scenarios are in what can be considered as diverse and green ones.

Within the same figure, the differences, represented graphically, regarding the percentage of people exposed to noise outdoors (left) and the total number of them (right) is appreciated. The UC and CAMP scenarios have a good performance regarding the diversity land use indicator (D_{LU}): both have similar percentages of people exposed to noise outdoors ($EO\%_{\mathrm{Ld}}$). However, when total numbers of people exposed to noise are studied, the CAMP scenario holds a higher number (2363), compared to UC (1659) (see *Num EO (Ld)* results).

Fig. 5.4 details the total number of people exposed and the percentage of D_{LU}: residents (left), all users indoors (centre), all users outdoors (right). A positive correlation is found, and a higher percentage 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). The previous brings further considerations when studying diversity and the consequences within the environmental quality. In this sense, outdoor noise exposure of people is generally ignored when studying health and wellbeing issues. Difficulties in such types of studies might be the reason together with the fact that Europeans spend the majority of time indoors (90 %) [94]. However, it has been proven that outdoor attractive sound environments can help as restorative places, moderating noise response [95] and probably other negative responses, e.g. stress.

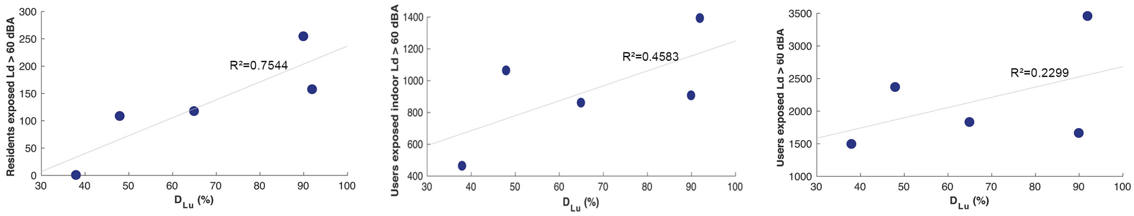

Figure 5.4: Correlation between the number of people exposed to noise ($L_d > 60$) and diversity of land use indicator (D_{LU}). Only residents (left); all users indoors (centre); all users outdoor (right).

What interests us with this type of analysis is the fact that there may be cases where changes in traffic volume are not as relevant to the impact of noise as the urban form characteristics. Other variables as behavioural or economic ones can impact on the behaviour of transport itself.

5.3.2 Density influence

The influence of density has been studied in the past years as one of the main characteristics of urban form, especially in the struggle between sprawl or compactness in cities (see for example [43,96–98]). In addition to what is presented in Paper VI, user and resident densities (person/km^2) are studied as interesting features of the urban form interacting with people's exposure to noise. The exposure is presented in both proportion and total number of people (see Fig. 5.5).

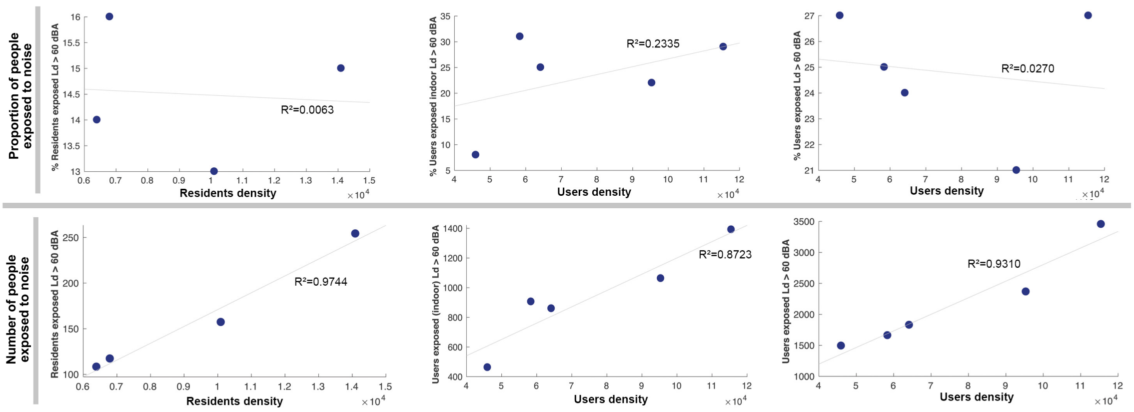

Figure 5.5: Comparison of correlations with proportion (top) and number (bottom) of people exposed to noise ($L_d > 60$) at each scenario with density for person/km^2.

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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 ended up in similar proportions of people's noise exposure. The density can then be used as a parameter to indicate the possible number of residents and users affected by noise. However, when we study the proportion of exposed people, the density does not yield more information about it.

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 spatial configuration.

5.3.3 Resilience behaviour outcomes

Further comments are presented here about the resilience behaviour analysis regarding the transportation system and its study through the acoustic variables. The reserve margin of housing depreciation to the total building stock value (for $L_{dn} > 55$ dB), represented as $RM_{T,P}$, shows that all scenarios have a certain housing depreciation, however, the UC is most affected (see Table 5.4). This could possibly respond to the intrinsic characteristics of the scenarios, as they are not substantially varying their urban layout: they try to re-use buildings and respect the major part of the traffic planning layout.

	$\%RM_{T,P}$			
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 5.4: $\%RM_{T,P}$ 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 as follows (Fig. 5.6):

- D_{LU}: within the reserve margin analysis of external costs due to residents' noise exposure, $RM_{T,C}$, and land use restrictions ($RM_{T,L}$), scenarios located at the upper left address a diverse but fragile scenario, meaning higher cost and land use restrictions due to noise, while the upper right reflects diverse and more robust ones. The differences between the scenarios are rather small in terms of reserve margin. Within the development capacity represented as land use restriction due to noise exposure ($RM_{T,L}$), 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.

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

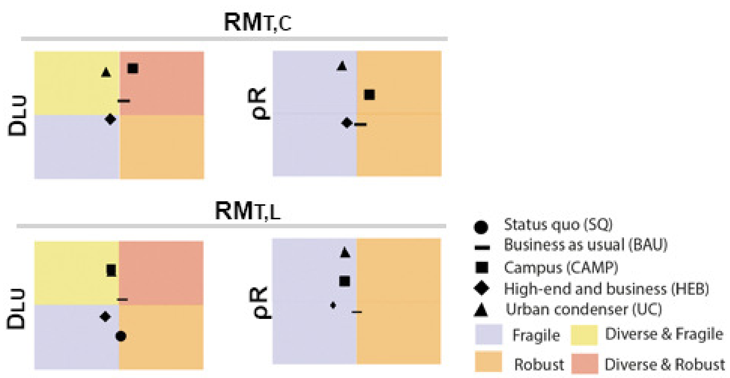

Figure 5.6: Indicators for transportation system resilience: reserve margin analysis of external costs due to residents' noise exposure, $RM_{\mathrm{T,C}}$ and $RM_{\mathrm{T,L}}$. Estimation on the reserve margin on the x-axis and diversity of land use (D_{LU}) and resident density (ρR) on the y-axis.

5.3.4 Final comments

Since urban planning directly affects the quality of life of its citizens, it is reasonable that a better understanding of the tension between spatial heterogeneity and performance would support decision-making in urban planning. From the scenarios tested, it is observed that spatial heterogeneity does not have a clear effect on environmental performance regarding the acoustic environment. It seems that increasing spatial heterogeneity does not go against good performance or resilience behaviour in terms of the 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. We already know that reducing noise at the most exposed façade requires a large effort, especially in consolidated urban areas. 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.

The validity of the conclusions is restricted to the range of tested scenarios, however, the methodology applied can be used to study future urban implementations. In the present study, the reuse of buildings restricts the differences between them, however, it gives credibility to the plausible scenarios. Also, the high flow of traffic in major urban arteries is maintained between the different scenarios. Therefore, boundary conditions and scale are crucial for this type of evaluation: a change in approach to a larger or smaller scale can give high or low degrees of spatial heterogeneity response, which must be taken into account.

A trans-scale evaluation would be extremely beneficial for understanding the interactions described above. Also, in the present study the effects of one of the chosen environmental indicators or another are not analysed, however, the interaction between them could greatly enrich the results of the study.

These interactions are only showing a small part of the big picture. The number of agents involved in the decision-making process and the production of cities is significant. Assessing urban, social, technical, sensorial, economic and ecological aspects, among others, and their combination, is vital in the built environment analysis. 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 fulfil both air and acoustic quality recommendations. In any case, the interaction between the transport system and the urban form and, more concretely, with the spatial heterogeneity could give answers to reduce this responsibility and improve the urban space.

Chapter 6

The sound environment assessment and the urban space

One of the main actors shaping the environment are the citizens. Moreover, they are not only shaping it, but giving meaning to it. The final goal of all the studies presented in this thesis is to make liveable spaces, places to enjoy and to improve the quality of life of the citizens while pursuing a good sound environment. Paper VII aims to understand the use of common space and how the sound environment affects its use, and how we can, as urban sound planners, enhance its design and use.

6.1 Introduction

Cities are experiencing a drastic transformation as citizens demands are increasing regarding the utilisation of space. Encouraging pro-environmental behaviour is a needed reality. However, human behaviour might be reluctant to change if we, as responsible of the urban development (planners, acousticians, politicians, etc.) do not provide the infrastructure for that. Structural and informational changes [99] need each other; e.g. reducing private vehicle use largely depends on the public transport alternatives provided. The same with socialisation in the common space: interconnected processes and decisions might promote socialisation activities. The challenge is to design contextualised urban spaces that correspond to their intentional use, providing and promoting quality from a holistic point of view, while being able to adaptively change.

This challenge involves directly the urban sound environment, as one of the pieces in the urban planning process. If it is considered as a self-evident part of the planning process, more opportunities will arise, since the sound environment is capable of providing new activities or enabling them along with other features of the site.

In the present study, the aim is on identifying the urban sound environment affects the uses and functions of common spaces and how it interacts with other spatial and environmental variables. The main question reads: Is there a certain sound environment required or that should be avoided when designing a space for a specific activity?

6.1.1 Possibilities to study the urban sound environment in the city of Gothenburg, Sweden

The city of Gothenburg, in which the study took place, has proposed that all parks and green areas have noise levels below 50 dBA (L_d) by 2020 in most of the park area [100]; however, when the study was conducted, none of the selected areas met this requirement, either on the levels presented by the city strategic noise maps or on the sound recordings made in the present study. This presents a great challenge for the city, urging the recovery of the sound environment of existing areas; but it also presents a great opportunity for developing interconnected methodologies that make use of the available tools: we must be able to guarantee citizens a good sound environment in the production of new public spaces.

As we have already mentioned in the previous chapters, the main tool used to investigate the urban sound environment are the noise maps provided by the cities. However, it has been proven that the information presented by these maps is not suitable for the general public, the urban planners and other relevant stakeholders [101]: they are difficult to interpret, they hold information exclusively from road and rail traffic, industry and aviation sound sources and the calculation methods (sometimes controversial as they are not intended to assess certain qualities such as shielded inner yards, see Chapter 3) and inputs vary, making comparisons between cities extremely difficult. However, they are a good tool as a first approximation to study the urban sound environment. For that reason, we want to explore the usefulness of such maps, combined with other tools, to predict suitable activities in urban common spaces.

In this sense, another tool used by the city regarding the study of suitable activities in the urban environment are the sociotope maps (representation of activities linked to the experience of a place). Previous research has partially shown their utility [102]. These maps may also bring further knowledge regarding the urban sound environment assessment and how it can influence the utilisation of a certain space.

The combination of resources as noise maps and sociotope maps, together with the development of tools (questionnaires evaluating quality judgements, particular sound quality attributes and suitability of activities) and sound recordings plus indicators, can help us to further understand the relevance of the outdoor sound environment in the spatial production and the functions of those spaces. As we have already mentioned, this is another step in the attempt to evaluate the urban sound environment through a multifaceted perspective.

6.2 Further remarks, limitations and open questions

In this chapter, no results/outcomes section is presented; for that, refer to the final section, *Concluding remarks* from Paper VII. However, we present a brief feedback on the main research questions, along with a series of limitations and pending questions based on the research carried out.

According to the previous paragraphs, the selection of the sites was performed based on three aspects: average noise level indicated by the Gothenburg noise maps, from 2013; the number of activities presented by the city sociotope maps, from 2006; and the main spatial character of the sites: urban, park, etc., as show in Fig. 6.1. The idea was to choose a wide range of sites in relation to these three aspects. However, another criterion to take into account was that in the chosen places we could find a sufficient number of regular users to complete the questionnaires, which limited the places mostly to the city centre. Sites with a low (<5), medium (5-8) and high (>8) number of activities and a variation in day-time equivalent levels in the three ranges 50-55, 55-60 and 60-65 dB, were wanted. However, a site with a high average level and a high number of activities was missing, being a first indication that when high noise levels are present, fewer activities are possible.

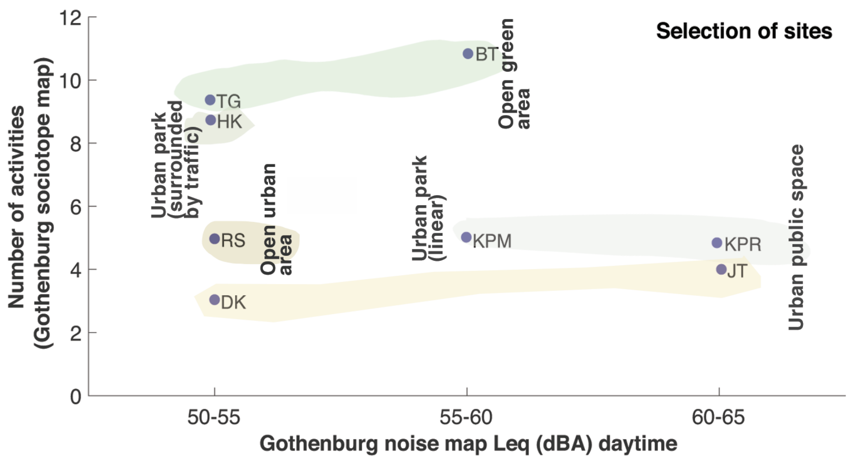

Figure 6.1: Sites, number of main activities and noise levels.

The selected sites around the city of Gothenburg and their locations are shown in Fig. 6.2 and Fig. 6.3. Sites 3 and 4 (Kungsparken) correspond to the same site, however, different weather conditions; site number 10 (Odinsplatsen) was introduced after the first selection criteria, as it did not appear in the sociotope maps or in the noise maps. Its introduction responded to the need of finding a site with relatively high noise levels, presence of vehicles and nature elements.

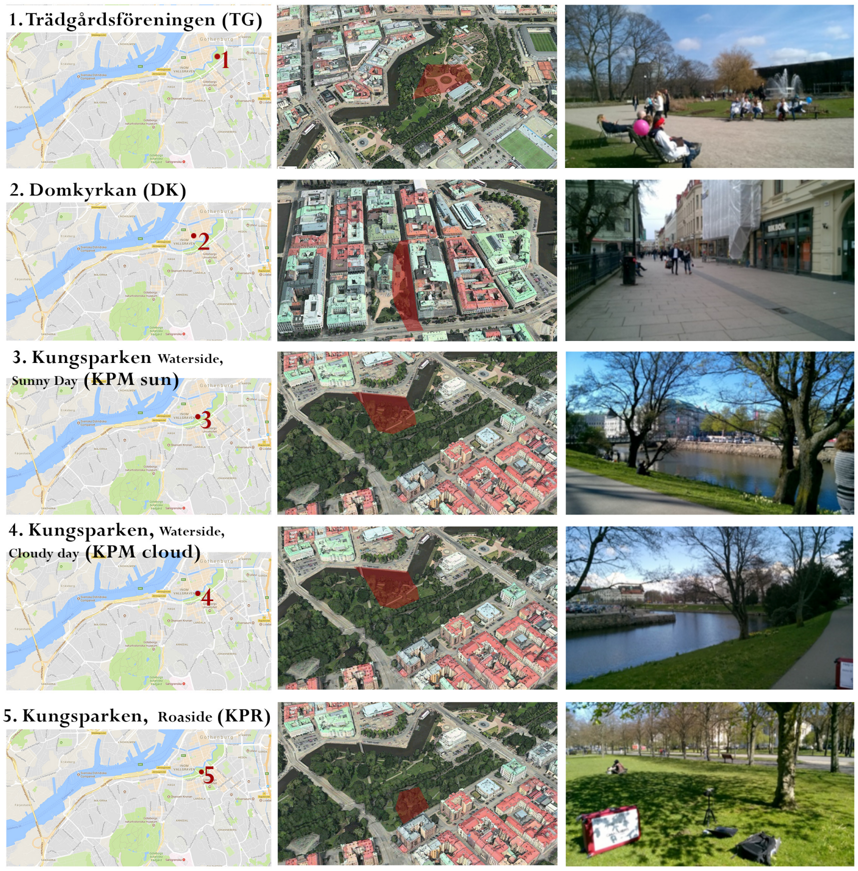

Figure 6.2: Locations 1 to 5: 1) Trädgårdsföreningen (TG), 2) Domkyrkan (DK), 3) Kungsparken sunny day (KPM sun), 4) Kungsparken cloudy day (KPM cloud), 5) Kungsparken roadside (KPR).

Figure 6.3: Locations 6 to 10: 6) Hagakyrkan (HK), 7) Botanical garden (BT), 8) Röda Sten (RS), 9) Järntorget (JT), 10) Odinsplatsen (OP).

The English version of the questionnaire is presented at the end of this chapter. It is based on previous questionnaires, however, there are several questions that might be improved. For example, further investigation is needed on the different activities asked for as suitable ones; the question ‘Are the following activities applicable to the location?’ presents an overlapping between the following activities: ‘Hang out, chat, talk’ and ‘Socialise with family and friends’. A positive correlation was found between them (0.82; $p<0.01$). The same occurs with the silence activities ‘Appreciate quietness and tranquillity’ and ‘Escape from city stress’ with a strong positive correlation (0.92; $p<0.01$) (see trend in Fig. 6.4). Similar phenomena happen between ‘Picnic’ and both ‘Appreciate parks and trees’ (0.83; $p<0.01$) and ‘Socialise with family and friends’ (0.90; $p<0.01$). However, this overlapping might also help to check if respondents understood the presented questions.

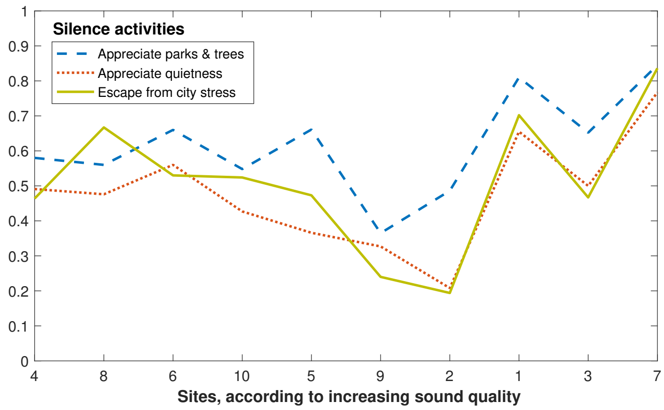

Figure 6.4: Silence activities rating according to increasing sound environment quality.

Overall quality and visual quality assessments seem hard to interpret independently. As we previously stated, the main planning interaction with the city is through seeing, and the overall evaluation of quality is also dominated by visual stimuli. In this context, perhaps asking about the overall quality means reflecting about visual aspects. Better questions, specific instructions, or training about the meaning of overall quality, is needed.

Going into detail about the sound environment evaluation, one of the main questions that we are interested in is the relevance of physical, environmental and perceptual variables to improve the overall and the sound quality of a place. Context and contextuality are one of the main subjects when studying human behaviour. Physical and psychological contextuality have been described as relevant for the auditory perception. Finding the right questions and adjectives to ask untrained 'on-site' participants remains a challenge. Are the attributes presented to them understandable? Several investigations have been carried out without a clear answer. Arguments have been presented in favour of perceived loudness as an immediate response to exposure to sound, postulating it as a better alternative than perceived annoyance [103, 104]. In our research, and with the limitations already explained in Paper VII, even though significant correlations were not found, perceived loudness, acoustic indicators as L_{A5}, L_{A50} and measured loudness, followed the same trends: as the noise level increases, the perceived loudness did as well. This was not the case for the adjective 'annoying'. It seems that our findings are aligned with the research previously mentioned arguing in favor of perceived loudness as a more appropriate question to understand the sound environment perception.

Researchers have also argued in favour of the sound environment quality judgement through its appropriateness to a place [105,106]. Others, as Axelsson [107], have questioned this, arguing that when appropriateness of the sound environment is the only parameter investigated, it can lead to sound environment misjudgements, qualifying it as a high quality sound environment, when in reality it might be a poor one (e.g. it might be 'appropriate' that a very busy street area is extremely noisy). Thus, should the sound environment be studied in terms of high quality independently of its appropriateness? Is this having an influence on the physical and psychological human mechanisms and on the way citizens are using common space? Is it enough if people feel that the sound environment is appropriate? Appropriate to what? Many questions are still open and further study is needed.

It has always been taken for granted that environmental factors as temperature influence human perception, and regarding sound environment perception, conclusions have been drawn (e.g. [108]), however, further investigation is needed to understand joint effects of environmental factors understood as potential stressors. In this sense, physical contextuality and environmental conditions appeared to be relevant at the same site, evaluated in two different days under different weather conditions, however, in the same season (late spring). When L_{Aeq} was 5 dB lower and better weather conditions were present, quality and judging attributes with higher intensity. Is the 5 dBA the only aspect that influences such judgments? What about the variation of plausible activities to be carried out in the same place? We believe that the variation in activities has an impact that comes directly from changes in weather conditions. In this study, this impact is presented, however, we cannot affirm that the influence comes from a single one of the reasons mentioned above or from a combination of them. In addition, user background and variation in sensitivity also influence the results. As stated, more studies and larger population samples are necessary for answering these questions.

As feedback from the study, the research questions proposed in Paper VII are answered briefly. For further conclusions, see section *Concluding remarks* from Paper VII.

- Is there a certain sound environment required or one that should be avoided when designing a space for a specific activity? Is it possible to predict? From the present study, we can argue that certain conditions are needed, however, further studies including larger samples and more locations should be made.
- What is the relationship between the overall quality, visual quality and sound quality? Overall and visual quality can be assessed as one unique item. Sound quality followed the same trend as overall and visual quality: when one increases, the others do too.
- Do sites have an influence on the suitable activities to be carried out? Can clusters of sites (i.e. locations with similar purposes due to its physical and perceptual features) be recognised? As a consequence, could such spaces have

similar uses and functions? Mainly, sites characterised in this study as urban sites can be distinguished from the rest regarding suitable activities. Further investigation is needed.

- Can sociotope maps help to predict suitable sound sources? Not yet. First, further development is needed to successfully capture users' experiences in the sociotope maps.

- What is the relation between the urban sound environment and the uses and activities performed? Quality of the sound environment appears as a complex attribute. For example, sound quality and its relation to silent activities or presence of mechanical sound sources is not straight.

- Can suitable activities be predicted from the information granted by the road traffic noise mapping results provided by the city or do we need fuller understanding of the urban sound environment? We can identify trends (tranquil/vibrant activities), however, it is better when sound recordings, including all sound sources, are performed.

With the present study, we look towards the expansion of current noise policies, going beyond their view of noise level reduction, moving towards pro-environmental behaviour in multiple aspects, both in planning development and within end users. For that, expert collaboration is desired. We pursue a higher level of awareness by providing tools and information, both to the agents involved in the entire urban process, as well as to citizens as end users. For example, this type of analysis might end up in a sociotope-environment map tool incorporating in this case, environmental sound assessments (but also other assessments as air quality, topography, mobility, monetary aspects, etc.). The intention is to enhance (not constrain) the urban development and bring further knowledge to successfully capture the users' experience of the city.

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0. Current time: ______________________

1. How often do you visit the location?
□ Every day
□ 2-4 times per week
□ 1 time per week
□ 2-4 times per month
□ 1 time per month
□ Less than 10 times per year

2. What is the average duration of the visit?
________ minutes or _________ hours

3. What is the purpose of the visit?
□ Reading
□ Children
□ Pets
□ Walking
□ Sports
□ Nature
□ Tranquility
□ Meeting friends/relatives
□ Shopping
□ Travel
□ Other __________________

4. What is the quality of the area as a whole? Mark on the stripes

0-bad 10-very good

5. What is the visual quality of the location? Mark on the stripes

0-bad 10-very good

6. What is the acoustic quality of the location? Mark on the stripes

0-bad 10-very good

7. How close is the location to your house (choose the mode of transportation you most often use to get to this location)?
□ < 5 min □ by foot
□ 5-10 min □ by bike
□ 10-15 min □ by tram
□ > 15min □ by car

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8. Are the following activities applicable to the location?

	Not at all	Slightly	Moderately	Very	Perfectly
Play informal games, Group exercise, collective sports like soccer or group fitness	☐	☐	☐	☐	☐
Appreciate cultural heritage	☐	☐	☐	☐	☐
Appreciate parks and trees	☐	☐	☐	☐	☐
Experience vibrant street life	☐	☐	☐	☐	☐
Hang out, chat, talk	☐	☐	☐	☐	☐
Appreciate watercourses	☐	☐	☐	☐	☐
Socialize with family and friends	☐	☐	☐	☐	☐
Appreciate quietness and tranquility	☐	☐	☐	☐	☐
Escape from city stress	☐	☐	☐	☐	☐
Picnic/barbeque	☐	☐	☐	☐	☐
Jogging, running or other individual exercise	☐	☐	☐	☐	☐
Shopping	☐	☐	☐	☐	☐
Travel, passing through	☐	☐	☐	☐	☐
Other:*	☐	☐	☐	☐	☐

*____

9. Do you find your surroundings organized? Mark on the stripes

not at all — slightly — moderately — very — extremely

10. How clean do you find the surroundings? Mark on the stripes

not at all — slightly — moderately — very — extremely

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11. How safe do you feel? Mark on the stripes

not at all — slightly — moderately — very — extremely

12. How appropriate is the sound to the surrounding? Mark on the stripes

not at all — slightly — moderately — very — extremely

13. How loud is it here? Mark on the stripes

not at all — slightly — moderately — very — extremely

14. For each of the 8 scales below, to what extend do you agree or disagree that the present surrounding sound environment is … (Please tick off one response alternative per scale)

	Strongly agree	**Agree**	**Neither agree, nor disagree**	**Disagree**	**Strongly disagree**
Pleasant	□	□	□	□	□
Chaotic	□	□	□	□	□
Vibrant	□	□	□	□	□
Uneventful	□	□	□	□	□
Calm	□	□	□	□	□
Annoying	□	□	□	□	□
Eventful	□	□	□	□	□
Monotonous	□	□	□	□	□

15. Please, list sound sources you noticed in descending order starting with the most noticeable sound source. Any number of listed sound sources is possible, but limited to 5.

1. ____
2. ____
3. ____
4. ____
5. ____

General information

Age:_______________ Gender: Male / Female
Occupation: ____
Do you have normal hearing? Yes / No
Highest completed level of education:_________________________
Optional: Comments (length of questionnaire/clarity of questions/etc.)

Chapter 7

Citizen perspective. Conclusion

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

John Friedman

Cities always face transition and adaptation, whether due to demands or needs. The twentieth century demanded an adaptation of the city's structures (some with better results than others) upon the arrival of the car. Today, additional adaptation is needed, as demanded by society; cities have in their hands numerous environmental challenges: according to United Nations data from 2018, they occupy 2 % of the earth's surface [109], are home to 55 % of the population, emit 71-76 % of greenhouse gas effect and use 67-76 % of global energy [109]. Within this context, it seems that 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 in terms of sustainability indicators such as accessibility, quality, health, nuisance and mobility, etc. [110]. In this regard, urban space quality assessment needs to include accurate sound environment studies capable of interacting with urban planning concepts as infrastructures, land use, urban design, public space, housing and citizen perspective, among others. This assessment demands also to pay attention to the functions and uses of those spaces.

And this is the main aim of the present thesis:

To improve urban processes and the built environment with respect to the sound environment by facilitating the closing of the gap between urban practice and the current situation in cities.

Diagnosing good qualities in any urban project requires more than an attractive image; we need to learn to respond to what the urban space demands and what people demand. The multifaceted perspective is not an option anymore, but a duty and a compromise. Under this perspective is where the acoustic environment needs as well to be understood as a fundamental part of the study of the urban environment. It seems that getting closer to decision-makers is one of the keys. The inclusion of real applications is probably an asset in the successful communication with all partners involved.

We attempt to guarantee a careful planning, going beyond today's standard approaches. For that, innovative and integrated approaches are required. However, these innovative approaches and the developed tools are useless if they are not capable of reaching their final goal: their implementation into real urban projects in order to improve citizens' quality of life.

For that, all agents involved in the production of space must step back and rethink about the consequences of their decisions. We need to avoid sub-optimisation and unnecessary economical and societal burden to all partners. Long-term perspectives, contextualised and trans-scale studies, co-productive actions, space adaptation and civic interaction are demanded from the urban environment.

That implies that the urban sound planning becomes a self-evident part of the production of space (Fig. 7.1). For that, we aim for a proactive urban sound planning where there is no single solution for all built environment. The synergies and combination of tools and approaches might be capable of improving expert decision-making that could enhance the current urban practice. There is still a long way to go, and this thesis attempts to give ideas to rethink about it.

Figure 7.1: Overview of the concepts involved in urban sound planning, represented through a sectional layout of a city.

7.1 Conclusions of Chapters 2–6

Study on the practical implementation of the urban sound planning concept

Our first study (Chapter 2 and Paper I) looks toward a practical implementation of innovative solutions on the study and improvement of the urban sound environment going beyond the scope of the current urban planning practice. The intention is to get advantage of the inclusion of urban sound planning in the city development process. Our main challenge, apart from the novel tools to study the sound environment with a holistic approach, was to connect relevant stakeholders (policy makers, politicians and staff from the urban and environmental city departments) with the different aspects of liveability regarding urban sound planning. For that, we studied four test sites at four different European cities with a different problematic regarding the acoustic quality. Particular approaches, adapted to each of them were developed. In this thesis, the particular technical solutions are not the interest, but the way we approach the studies.

One of the most valuable aspects of the urban sound planning approach is its final purpose: making urban spaces more habitable; this vision is shared with the urban planning process, which, in principle, would guarantee communication and understanding between the different agents. However, the SWOT analysis presented in Paper I reflects the difficulties in the whole process regarding the improvement of the urban sound environment. The following lines try to exemplify some of the opportunities and threats we encountered at each test site.

For the Antwerp Rivierenhof Park, the working group held different professional backgrounds, the same was the case for Brighton Valley Gardens. However, Antwerp working group had an indirect contact with the city representatives, while the Brighton group had direct contact with the city project manager and design team. This fact changed completely the way the problem was approached, the results and of course, the implementation. Also, the Frihamnen Gothenburg working group did not have direct contact with the design group or the traffic planning team, hence were not part of the decision making process; the same as in for Rome Colosseum test site, with the difference that the last one did have the support from the government.

The main threat in all test sites was that the recommendations provided regarding the inclusion of urban sound planning were not considered in the city's proposals. Increasing environmental degradation due to this lost opportunity is a fact, and after these years, we have corroborated it. An exception is the case of Valley Gardens, in which the sound environment is currently studied at the site, following the recommendations of the SONORUS working group.

With this research we attempt to raise awareness about the importance of including the sound environment in the urban planning development, no matter if it is a new area (Frihamnen, Gothenburg), a small park (Rivierenhof Park, Antwerp), a consolidated part of the city (Valley Gardens, Brighton) or a historical site (Colosseum, Rome). We also want to highlight the difficulties encountered, not only technical, but moreover, regarding the inclusion of the sound planners as an active part in the whole process.

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

With the previous study, we corroborated that a careful planning needs to account for accurate noise assessment results. When looking at the impact these assessments have on the urban development, granting access to a shielded area has great consequences in the decision-making urban planning process. In Chapter 3 and Paper II, 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 of closed courtyards, a total underestimation reaching 15 dBA can be found when only the first reflection is included. When considering multiple reflections, the agreement is better, however, incrementing the number of reflections 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 for the studied cases. 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, especially in the current densification process that cities as e.g. Gothenburg are going through. Further work is needed, although the first steps have already been taken [59], primarily in the automation process to model complex scenarios.

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

In every city, all kinds of transport modes are submitted to a vast amount of interactions with pedestrians, traffic lights, other vehicles, as well as to different driving behaviours, etc. Time-patterns and vehicle kinematics are of great importance in the study of the outdoor sound environment and noise annoyance. However, noise mapping tools have been assuming a constant traffic flow for their assessments. This fact obviously differs from current situations in cities, and is concluded to be of importance.

The third study, presented in Papers III and IV, as well as in Chapter 4, aims for the development of a tool capable of incorporating the influence of vehicle kinematics in the acoustic assessment. For that, the developed tool uses individual vehicle records in terms of location, acceleration and velocity, as function of time. Through a series of *Matlab* scripts, the output source strength of each vehicle is estimated as function of time, depending on vehicle type, speed and acceleration. Three vehicle types (light, medium-heavy and 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 uses peak hour real future scenarios within the city of Gothenburg, Sweden. In an attempt of being as close to reality as possible, the intention of the investigation presented in Paper III and Paper IV was always to be able to hold the same amount of traffic as the original plan. As results, the sound environment analysis is presented through dynamic maps and contribution maps, statistical indicators and time-pattern analysis. The last one includes calm periods and noise events. It should be noted that the tool allows for other indicators to be studied than those included here.

Paper III is focused on the overall development of the tool within a large case study known as the Frihamnen area, in Gothenburg, Sweden. Eight different scenarios were proposed based on the plans that the city administration had at that time. Among the results, the banning of heavy vehicles or the suppression of acceleration values within the base scenario (the one proposed by the city administration), were shown to result, in average among the 11 study points, in moderate and very similar reductions of equivalent sound pressure levels (1.5 and 1.9 dB). Larger differences were found with the maximum levels (L_{max}), with average reductions of 3.4 dB for the scenario where heavy vehicles were banned, and 1.5 dB for the suppression of acceleration.

A second interesting study concerns the number of events. They are studied as an indicator capable to evaluate interference with human activities and noise annoyance. Noisy events may be misrepresented by the equivalent sound pressure levels. As an example, a similar equivalent sound pressure level was found among certain study points (points 6 and 7), with differences of around 1-2 dBA (6: close to an intersection and 7: close to a road with a 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 63 to 39 in study point 6 and from 12 to 2 in study point 7.

A novel indicator, named Centre of Mass Time (CMT) intends to weight the cluster of quiet periods, rewarding having few larger quiet periods than many short ones. Paper III introduces the indicator to compare the different scenarios. In this case, study point 1, close to a busy highway, values go from +7 to -4 seconds relative to the base scenario (33 s), with the limit value being the median level L_{50}. For study point 1, the best scenario concerning CMT L_{50} is scenario 5 (+7 s), where the speed on the highway is reduced and longer quiet periods appear. Contrary to scenario 8 (-4 s), with only light vehicles present and shorter quiet periods.

Graphical tools are also of relevance for the communication with stakeholders and implication of other agents involved in the multifaceted perspective of the urban sound planning study. Graphical contribution maps, based on time patterns, are presented 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.

Paper IV goes into close detail of a traffic intersection, and the dynamic traffic noise tool was further developed. The study transforms a signalised crossing intersection into a roundabout. Results show that, for example, when modelling the peak hour scenario, both simulations are heavily congested, and the roundabout experiences serious drawbacks in terms of noise pollution. When banning heavy vehicles, the signalised crossing ended up being more efficient in terms of equivalent sound pressure level. Also, reducing the traffic flow by 25 % within a configuration of light vehicles was shown to give results as expected from common noise mapping techniques in the long-term L_{Aeq} (i.e. a reduction by 1.25 dB). However, when heavier vehicles are present, this reduction gets 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, since due to the principle of yielding to circulating traffic, the roundabout may perform worse than the signalised crossing for several of the indicators studied.

A different graphical tool is also presented here, called the difference map (between the two types of intersection). Results show that in the case of all entry lanes clustered into one, and the same for the exit lanes, the crossing intersection type is noisier 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.

For the moment, the tool is within a flat city, and this simplification is valid for the current purpose of analysis. Also, air attenuation is not incorporated and future work on this will allow reliability at further distances. Furthermore, the 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 also, the urban layout in which these vehicles will exist.

The tool can be combined with other space matrix descriptors, in an attempt to study different spatial configurations that respond to the functional demands. For example, we can estimate the sound power level per unit area. With this idea in mind, the extension to the urban form and other system interactions is missing. In an attempt to study these interactions, the following study was carried out.

Study on the urban form and the environmental performance

For many years, the built environment has been analysed with a fragmented view. However, this type of analysis is not only exposing our cities to a short-term failure, but moreover to a major problem with effects through time and scale. This might be partially due to the fact that the urban form does not have the capacity to change as rapidly as the function of space. In this context, the production of space can be enhanced or diminished by the interaction between urban systems. Two of the main urban systems are transportation and energy, having great implication on the quality of the built environment (air and acoustic quality) and hence, on the quality of life. Moreover, both of them are part of and constantly interacting with the urban form.

The term resilience has been rapidly incorporated in the urban planning wishes, impacting on the resulting environment. The spatial heterogeneity is of interest as a positive property for resilience behaviour. The constant interaction of the energy and transportation systems with the urban form, and hence, the spatial heterogeneity, is theoretically discussed in Paper V. As a continuation, Paper VI and Chapter 5 present the above ideas through the study case of a real scenario subjected to transformation in the city of Zug, Switzerland. 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}). The sound environment is analysed through several indicators, e.g. the share of people exposed to noise during daytime (both indoors and outdoors), the share of quiet areas and the share of residents highly annoyed. For this particular case study, the spatial heterogeneity did not have a clear effect on the environmental performance regarding the sound environment.

To illustrate the possibilities that these types of analyses have, selected conclusions are presented here. 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 positively correlated with a higher land use mix index (D_{LU}). 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. Nevertheless, the impact on other areas of the city will need to be accounted for, e.g. consequences of scattered or high-density urban developments. 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.

To continue the analysis, 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 translated into a social cost reduction. This will bring a more robust and adaptive economic analysis. 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). Analysing each scenario, the Urban Condenser (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 of land use is not giving a higher risk in terms of social costs due to noise. We can conclude 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.

More robust results regarding the interaction between spatial heterogeneity and environmental performance are needed, as limitations are present. The tested scenarios were quite similar regarding the shape of buildings and spatial location; they intended to be as realistic as possible. Incorporating drastic changes could end up in more clear results regarding the interaction between spatial heterogeneity and environmental performance. Also, the disruptive events assessment of the modelled scenarios and the study of spatial processes in the area are needed, including time and scale aspects.

Study on the sound environment assessment and the urban space

When we look closer into the city, the design of public common space should respond to several urban systems interactions: the geographical and environmental aspects, the context, the purpose and the needs that citizens have. Sometimes, part of these interactions is ignored or misjudged, or considered once the space is already in use. The last study presented in Chapter 6 and Paper VI looks toward the understanding and relevance of the sound environment in the use of common space. The main idea behind it is whether there is a certain sound environment required or that should be avoided when designing a space for performing a specific activity.

Nine common spaces from the city of Gothenburg were studied. The study includes the use of the city sociotope maps as they suggested a series of activities; also, noise maps from the city were included in the site selection. Sound recordings and questionnaires to regular users were performed. Several limitations are present in this study (i.e. small sample size and lack of understanding of certain adjectives by the participants), however, results are worth to explore and discuss; it seems that certain activities could be identified from L_{Aeq} values, with a vibrant/tranquil dimension; also, sound quality cannot be judged by asking about overall quality; however, visual quality seems to go along with overall quality. Measured and perceived loudness assessment varied. City noise maps seemed to be a good tool to start the analysis of suitable activities in common spaces, for example, in new development areas. However, to have a more accurate evaluation of the functionality of the space, recordings are needed, especially when studying tranquil activities.

7.2 Summarising conclusion

The results presented in this thesis are seen as a contribution to improve the urban sound environment from a holistic approach, but still being a small part thereof. There is plenty of room for improvement and further development not only of the tools (i.e. a combined tool capable of getting advantage of the synergy effects), but also of the approaches presented. With this work, we aim to contribute both to the professional practice and the academic field, from a manifold of tools targeting different spatial scales, different timing in planning, different problems and different fields of knowledge under the umbrella of urban sound planning. At each of the previous sections and papers, limitations are highlighted together with future work. However, there have been general limitations that are worth to stress, which mainly correspond to communication. From one side, the lack of transparency and facilitation of information of urban developments from all stakeholders, together with the outdated information, e.g. traffic data and sociotope maps, have impact on all the developed studies. These limitations are external to us in a way, but are reflecting where the effort is needed. On the other side, limitations to reach in some cases the relevant audience has also been a drawback. This has had consequences in the first mentioned limitation: if the relevant audience becomes interested, information has more chances to be facilitated. Future work is therefore not only going to be on improving the tools and find synergies (which is already a lot in itself), but moreover, on the communication improvement of the opportunities for the urban sound planning.

The present document is elaborated as a call for policy makers, urbanists, architects, acousticians, traffic planners, and others dealing with the concept of urban sound planning. With the intention to facilitate the use of these outcomes by the above-mentioned practitioners, a brief summary of the tools and approaches is presented in Table 7.1. Main tools, advantages and disadvantages (understood as future work) are also included.

Table 7.1: Synthesis of tools of the present thesis.

Study number	What?	Why?	Where?	When?	By whom? (first actors)*	By whom? (supporting actors)**
1. Chapter 2	STUDY CASES AND URBAN SOUND PLANNING	Better understanding of the opportunities and difficulties of the implementation of urban sound planning strategies.	New urban developments; consolidated areas with the intention to improve their urban sound environment; small areas with historical character; recreational areas; etc. Different spatial scales: macro, meso, micro-scale.	Different time frames: from planning stage to stages when noise complaints appear.	Policy makers, acousticians	Traffic planners, urban planners, health experts, social scientists.

- **Tools:** SWOT Analysis of urban sound planning approach.
- **Advantages:** Reflection of possibilities regarding urban sound planning. Different tools and recommendations presented. Going beyond noise levels as a ceiling. Interdisciplinary approach.
- **Disadvantages:** Lack of communication with relevant stakeholders: recommendations left in the drawer. The approaches may be influenced by the skills and interests of the members of the working group.

Study number	What?	Why?	Where?	When?	By whom? (first actors)*	By whom? (supporting actors)**
2. Chapter 3	QUIET SIDE AND NOISE MANAGEMENT (NOISE MAPS)	Need to develop accurate tools regarding noise calculation for closed courtyards. Implication on legislation: densification of cities.	New and consolidated urban developments. Meso and micro-scale.	Different planning stages: most convenient, during the planning stage of this building typology or in planning of densification of consolidated areas (filling 'gaps' in urban blocks). Also, when performing EU mandatory city noise maps and when noise complaints appear	Policy makers, acousticians.	Traffic planners, urban planners, architects, health experts, social scientists, real estate developers.

- **Tools:** Qside implementation model.
- **Advantages:** Improvement of noise calculation for closed courtyards (engineering method); better sound environment assessment.
- **Disadvantages:** Tool under current development (automation process currently explored). Further comparison with real scenarios. Not (yet) incorporated on commercial software. Urban morphology limitations (simplifications).

Study number	What?	Why?	Where?	When?	By whom? (first actors)*	By whom? (supporting actors)**
3. Chapter 4	CITY TRAFFIC PLANNING AND THE SOUND ENVIRONMENT	Road traffic noise studied through current noise mapping techniques are not including vehicles kinematics (no breaks, traffic lights, stops, etc), leading sometimes to inaccuracies. Need for tools and indicators.	New and consolidated urban developments that present road traffic as part of it: from neighbourhood scale to a small change in mobility patterns: meso and micro-scale.	Planning stage, but also when improvements are proposed in consolidated parts of the city that include either improvements in urban mobility and the sound environment, improvement of sidewalks, parks, changes in facades to improve the indoor sound quality, etc.	Noise management: acousticians and policy makers.	Urban planners, acousticians, architects, policy makers, health experts.

- **Tools:** Dynamic traffic noise assessment tool.
- **Advantages:** Better assessment of the influence of road traffic on the sound environment at closed distances, where kinematics is relevant.
- **Disadvantages:** Rigour and knowledge of mobility aspects. Complex tools. Flat city model. Noise indicators on development: missing appropriateness of them (auralisation and perception studies).

Study number	What?	Why?	Where?	When?	By whom? (first actors)*	By whom? (supporting actors)**
4. Chapter 5	URBAN FORM: TRANSFORMATION, DIVERSITY AND ENVIRONMENTAL PERFORMANCE	Study the diversity of urban form and the environmental performance. Bring better understanding of urban strategies as diversification and the impact on the environmental performance, and the consequences therof.	Transformation of current urban settlements, but also new urban developments. Meso-scale.	Planning stage of new areas and transformation of consolidated ones.	Acousticians, urban planners, policy makers.	Traffic planners, real estate developers, architects, health experts.

- **Tools:** Analysis matrix (indicators): Urban form (diversity), transportation and the sound environment (performance and resilience).
- **Advantages:** Knowing the consequences of urban form decisions on the environmental performance due to the transportation system and the consequence of such performance.
- **Disadvantages:** Tool under development; higher level of accuracy needed (study indicators and thresholds). Multidisciplinary knowledge needed.

Study number	What?	Why?	Where?	When?	By whom? (first actors)*	By whom? (supporting actors)**
5. Chapter 6	PUBLIC SPACE, USERS AND THE SOUND ENVIRONMENT	Better understanding of the impact of the urban sound environment in the use of public spaces.	Public spaces: parks, squares. Micro-scale.	Design of new public spaces. Also, when spatial and activity adjustments are going to be performed in public spaces	Urban planners, acousticians.	Policy makers, architects, social scientists, traffic planners.

- **Tools:** Questionnaire: common public space, activities and sound environment.
- **Advantages:** Identification of plausible activities at public spaces when certain noise levels are present. Assessment of appropriateness of the sound environment. Good result identifying activities accounting for road traffic noise.
- **Disadvantages:** Study under development (small set of cases and participants). Need of real data (recordings). Questionnaire improvement needed.

Notes on Table 7.1: *Principal actors: they are the first ones to study and intervene in the project. **Actors who also are essential but join the scene/project along the play. More actors (perspectives) may be involved, depending on the context, the project and its development, etc. The advantages and disadvantages mentioned are a small list of the main ones (further limitations and opportunities can be found at each of the chapters as well as in the appended papers).

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