BaLSaM – Audio-visual simulation of mesoscale urban design for sound-informed planning in the Rhenish mining region

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Abstract

Traffic noise is a major environmental health burden in European cities, yet it is often addressed at a late stage in urban planning processes, mainly through legally required assessments that use technical indicators and do not directly incorporate human perception. The BaLSaM project developed and tested an audio-visual simulation that links traffic data, auralisation and urban design to support sound-informed decisions at the mesoscale of neighbourhoods. In collaboration with four municipalities in Germany's Rhenish mining region, we combined parameterized urban design variants (building height and depth, block porosity, street layout) with noise simulations and listening tests in Virtual Reality (VR). This setup can be applied at the earliest stages of urban design, turning acoustic conditions and perception into design parameters, allowing non-experts to experience and evaluate possible acoustic futures.

The contribution presents: (1) the audio-visual VR framework, (2) illustrative findings on how mesoscale urban morphology affects exposure and perceived acoustic quality; and (3) lessons learned from applying the workflow in planning processes. We argue that combining noise indicators with perception-based assessment provides a practical interface between acoustics, urban design and municipal governance, and can support a shift from reactive noise control to proactive urban soundscape design

Keywords: *urban soundscape design, traffic noise auralisation, mesoscale urban morphology, audio-visual virtual reality, soundscape*

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1. Introduction

1.1 Traffic noise as an urban planning challenge

Traffic noise is one of the major environmental health risks in European cities. More than one fifth of the European population, around 112 million people, is exposed to transport noise levels above harmless thresholds, with considerably higher shares in many urban areas [1].

Today's noisy urban environment is a by-product of twentieth-century urban growth, functional separation and increasing traffic volumes [2]. Contemporary European planning responds to these urban development trajectories by promoting compact, mixed-use and transit-oriented urban forms that can reduce travel distances and car dependence. For housing development, however, this often shifts attention from greenfield urban expansion towards densification and transformation sites already exposed to significant traffic noise. At the same time, the intended proximity of housing, commerce, production and public life can intensify noise conflicts [3, 4].

Addressing these conflicts requires more than source-related measures such as lower speed limits, quieter road surfaces or vehicle regulations. Noise prevention also depends on long-term urban and transport planning strategies that shape where activities take place, how people move and how buildings, streets and open spaces are arranged [1].

1.2 Acoustic quality at the neighbourhood scale

Urban acoustics can be addressed at different spatial scales. Macro-scale instruments such as regional planning, land-use allocation, transport policy and strategic noise action plans shape broad exposure patterns, while micro-scale measures such as façade design, materials or landscape barriers modulate sound locally. Between these levels, the mesoscale is where urban design becomes relevant: neighbourhood layouts, street geometry, block structure, building orientation and the spatial organisation of uses directly influence how traffic noise propagates and how acoustic conditions are experienced [5, 6].

Although all three scales contribute to noise reduction, the mesoscale offers a particularly powerful yet underused opportunity to shape the urban acoustic environment. While macro-scale strategies define broad objectives and many micro-scale measures intervene late in the process, mesoscale planning translates goals into concrete spatial configurations early enough to influence acoustic conditions systematically. Yet the acoustic effects of urban morphology remain insufficiently studied and are rarely translated into everyday planning and design practice [7-9].

1.3 From technical assessment to perception-based planning

Despite the relevance of the mesoscale, several barriers hinder the integration of acoustic quality into urban design. First, planning practice remains strongly visually oriented: urban form is conceived and negotiated through plans, drawings, models and renderings, while acoustic qualities are difficult to anticipate and evaluate before a place is built. Noise simulations can be interpreted by experts, but are hard to experience for planners, decision-makers or future users, so sound rarely becomes an active design parameter in early-stage planning [10-12].

Second, beyond the proactive, citywide noise action plans required by the Environmental Noise Directive, traffic noise often enters concrete development projects too late. In competitions and early masterplans, it is usually treated as one boundary condition among many, but rarely translated systematically into urban form. Once projects reach statutory planning, formal noise assessments become central for legal compliance; however, key decisions on block structure, street layout, land use and building orientation have often already been made. Noise is therefore perceived mainly as a constraint on an existing concept rather than as a quality that can shape the concept itself [10, 13, 14].

Third, noise assessment remains dominated by quantitative indicators that are typically organised by source, for example road, rail or industrial noise. Noise maps and exposure metrics such as Lden are essential for regulation and comparison. However, these indicators, and the corresponding source-based legal frameworks, do not capture how people experience the combined acoustic environment, particularly in compact mixed-use neighbourhoods where multiple sound sources superpose [10, 11, 15].

These observations point to a research and practice gap: planning lacks tools that translate acoustic exposure and human perception into early-stage design decisions. The central question is how planning can move from treating noise as a by-product of urban development towards understanding sound as a design parameter, supported by methods that allow planners, designers, municipalities and stakeholders to test and compare how future places might sound [5, 6, 9, 10, 16].

1.4 The BaLSaM Research Project

The BaLSaM research project ran from 2022 to 2026 and brought together acoustics, automotive engineering, urban planning and practice partners. It was conducted by RWTH Aachen University's Institute for Automotive Engineering and Institute for Hearing Technology and Acoustics, HEAD acoustics GmbH and REICHER HAASE ASSOZIIERTE, with funding from the Federal Ministry of Transport and Digital Infrastructure within the mFUND programme. It developed and tested an audio-visual simulation workflow that combines traffic data, acoustic modelling, auralisation and urban design scenarios. Applied in real-world planning contexts in the Rhenish mining region, the project makes the acoustic effects of alternative urban forms and mitigation measures perceivable and comparable, enabling planners and municipalities to evaluate design concepts at an early stage [17].

1.5 Objective and contribution of this paper

This paper introduces an audio-visual planning framework developed within the interdisciplinary BaLSaM research project to integrate acoustic considerations into early-stage neighbourhood planning. Based on four case studies in Germany's Rhenish mining region, it presents the methodological workflow, illustrative findings on the relationship between mesoscale urban morphology, acoustic exposure and perceived acoustic quality, and lessons from its application in design processes. By bridging acoustics, urban design and planning practice, the paper contributes to a shift from reactive noise mitigation towards proactive, sound-aware urban design.

2. Method

The methodological approach was designed to test an audio-visual simulation workflow in real-world urban design scenarios and to examine how alternative morphological neighbourhood configurations affect both acoustic exposure and perceived acoustic quality. Four planning-relevant sites were selected in Düren, Merzenich, Grevenbroich and Titz. For each site, comparable urban design scenarios were developed with the municipalities, translated into 2D plans and 3D models. The scenarios were assessed through indicator-based noise simulations in Autodesk Forma and transformed into immersive audio-visual VR environments. Listening experiments were then conducted to compare selected variants from a perception-based perspective and to evaluate the workflow's applicability for early-stage sound-informed planning.

2.1 Case Study Context

The Rhenish mining region is shaped by lignite extraction, structural change and the planned coal phase-out, and is now undergoing spatial transformation. This affects not only former industrial and mining areas, but also towns, settlement edges and previously peripheral sites whose locational qualities are changing. As these places become candidates for new housing, mixed-use quarters or urban extensions, existing road traffic noise increasingly intersects with new demands for liveable and healthy environments. This makes the region a suitable laboratory for testing sound-conscious urban development.

Four case studies were selected based on concrete planning needs, road traffic noise exposure, scope for design variation and comparability: a former military/commercial site in Düren, a settlement extension in Merzenich, an expansion area in Grevenbroich-Frimmersdorf and an agricultural transformation site in Titz-Rödingen.

2.2 Urban Design Scenarios

For each case study site, comparable urban design scenarios were developed in close exchange with the municipalities. To structure the comparison, six design variants, as shown in Fig. 1, were defined, each systematically varying key mesoscale parameters such as building height and depth, block porosity, street layout and forms of shielding. Together, these variants examine how different neighbourhood configurations shape acoustic conditions through urban form, resulting in 24 research-oriented scenarios [18].

The baseline variant, illustrated in Fig. 2, represents a realistic, locally grounded reference scheme for each municipality. The "Closed perimeter" variant, illustrated in Fig. 3, tests a continuous built edge towards the main noise source, shielding more sensitive residential and open spaces in the interior. The "Angled and open" variant breaks up the street edge through diagonally positioned buildings, creating more differentiated reflection paths and acoustic zones. The "Shifted labyrinth" variant offsets and interlocks building volumes to test smaller-scale acoustic modulation and fragmented shielding. The "High rise" variant introduces additional storeys to examine the relationship between density, vertical exposure and shielding effects. Finally, the "Thick types" variant uses deep, compact building forms to explore whether greater building mass can protect exposed outdoor spaces.

The design variants were developed through an iterative co-design process with the planning departments of the four municipalities. These were partly adjusted for comparative analysis and should not be understood as politically agreed planning proposals or approved development targets. All scenarios were translated into 2D plans and 3D models for noise simulation, visualisation, auralisation and audio-visual listening experiments.

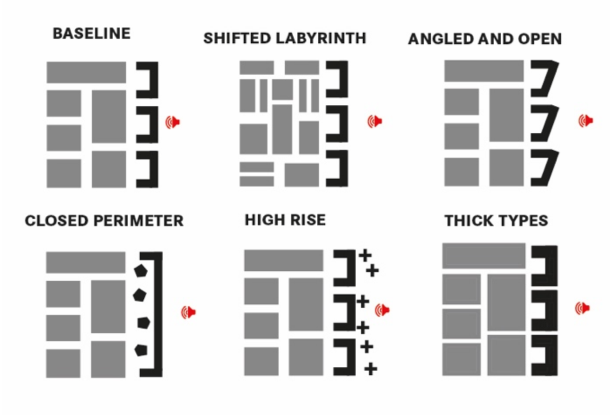

Figure 1. Six Urban Design Scenarios

Figure 2. Exemplary Urban Design Scenario Baseline (Düren)

Figure 3. Exemplary Urban Design Scenario Closed perimeter (Düren)

2.3 Noise Simulation and exposure assessment in Autodesk Forma

Noise exposure was assessed using Autodesk Forma Site Design. The 24 urban design scenarios were imported as simplified spatial models and compared through noise simulations based on the CNOSSOS-EU method. This allowed the variants to be evaluated using noise maps and quantitative sound level indicators. Simulations were carried out for the four study areas of Düren, Merzenich, Grevenbroich and Titz.

2.4 Immersive Audio-Visual Framework

For the audio-visual listening experiments, the urban design models were prepared as coupled visual and acoustic representations. The acoustic models were simplified, assigned material properties and simulated using geometrical acoustics. The resulting traffic noise was rendered in first-order Ambisonics to preserve directional sound information at the listener position. In parallel, visually plausible neighbourhood scenes were generated from the design variants and integrated into Unreal Engine, including façades, surface materials, vegetation and controlled vehicle movements. The auralised traffic sounds and visual scenes were synchronised within a VR environment. Head rotation and viewing direction were used to maintain spatial correspondence between the reproduced sound field and the visual scene. This setup allowed participants to experience and compare alternative urban design scenarios under controlled but immersive audio-visual conditions, as shown in Fig. 4.

2.5 Listening experiments

The listening experiment used Individual Vocabulary Profiling (IVP), a method in which participants describe audio-visual scenes in their own words and then use these self-defined attributes to rate and compare scenarios. To keep the experiment feasible and avoid excessive participant burden, it was limited to the six design variants of the Düren case study rather than all 24 scenarios. After an introduction and demographic questionnaire, participants explored the six VR scenes and developed auditory and visual descriptors. Each attribute was defined by lower and upper anchors and later used as an individual evaluation dimension.

In the second phase, participants rated the variants relative to each other using sliders. In addition to the self-defined attributes, pleasantness, annoyance and auditory, visual and overall preference were assessed. Visual stimuli were presented via VR headset, while auralised traffic sounds were reproduced via headphones. In total, data from 28 participants were collected, including 189 self-chosen perceptual attributes.

Figure 4. Experimental VR setup

3. Results: Illustrative findings on urban form, exposure and perception

The results are presented as illustrative findings from two complementary analyses: indicator-based noise simulations and the audio-visual listening experiments. Together, they demonstrate how mesoscale urban morphology can be assessed in terms of both calculated acoustic exposure and perceived acoustic quality.

3.1 Noise exposure: Urban morphology shapes traffic noise exposure

The comparative noise simulations in Autodesk Forma show that mesoscale urban morphology has a clear influence on calculated traffic noise distribution. Across the case studies, the “Closed perimeter” variant produced the most consistent reductions, demonstrating the shielding effect of a continuous built edge towards the noise source. The “High rise” variant also showed noise-reducing effects, although with diminishing additional benefits for each further storey. By contrast, the more open or fragmented variants, such as “Angled and open” and “Shifted labyrinth”, more often produced sound leakage and greater spatial variability in noise propagation.

Beyond the comparison of variants, the results indicate that distance to the noise source and the size and position of openings in the built edge are critical parameters. Wider gaps increase the risk of sound transmission and local exposure peaks, while offset secondary buildings can act as additional barriers, especially when they accommodate less noise-sensitive uses.

3.2 Listening experiment: Perceived acoustic quality in audio-visual context

The listening experiment, in contrast to the noise exposure simulation, focused on sound sources inside the neighborhood rather than on the main road along it. Consequently, the perception of the design variants did not simply mirror the calculated noise exposure. In the preference ratings, visual preference showed larger differences between scenarios than auditory preference, and the ranking of overall preference closely followed the visual evaluation. This suggests that, in immersive urban scenarios, the spatial and visual character of the design strongly mediates how the acoustic environment is assessed.

The results also reveal tensions between noise level reduction and perceived quality. The baseline scheme received the highest overall preference rating, but not the highest score for the pleasantness rating. Notably, the “Closed perimeter” variant, despite its strong performance in the noise simulations, received relatively poor ratings for pleasantness and annoyance.

The analysis of self-chosen attributes further supports this finding. The individual attributes were used to form perceptual clusters through hierarchical multiple factor analysis, allowing their relationship to the main components to be examined. Visual attributes formed more clearly separated clusters than auditory attributes, suggesting that participants differentiated the design variants more strongly through visual-spatial qualities than through auditory descriptors alone. This underlines the added value of audio-visual assessment: acoustically effective forms are not necessarily perceived as the most attractive urban environments.

4. Discussion

The findings provide two main insights. First, they show that mesoscale urban morphology can be deliberately used to influence traffic noise exposure and perceived acoustic quality. Second, they demonstrate that audio-visual simulation can extend conventional noise assessment by making alternative acoustic futures perceivable and discussable in planning contexts.

4.1 Urban morphology as an acoustic design parameter

The noise simulations across the four sites and the listening experiment for the Düren variants indicate that mesoscale urban form influences both calculated exposure and perceived acoustic quality. Parameters such as closed or partly closed building edges, building height, block depth, courtyard configuration and the position of openings can therefore be understood as acoustic design variables.

At the same time, the results show that these parameters cannot be evaluated in isolation. A closed building edge, for example, can effectively shield inner areas from traffic noise, but may also affect spatial perception and be experienced as defensive or constricting. Conversely, more open or fragmented variants may perform less favourably in calculated noise exposure, while being perceived more positively in an audio-visual context. This tension illustrates why sound-informed planning cannot rely on noise maps alone. Noise reduction effectiveness and perceived urban quality need to be assessed together.

This confirms the strategic importance of the mesoscale: decisions on street layout, block structure, orientation, density and quiet internal areas are made early, but set long-term conditions for the acoustic environment.

4.2 Added value of audio-visual simulation for planning

The testing of the audio-visual simulation workflow in real-world design contexts shows that it can be integrated into urban design scenarios to compare alternative configurations. The audio-visual workflow complements rather than replaces conventional noise assessment. Noise maps provide essential information on exposure patterns and regulatory compliance, while audio-visual simulations add a perception-based perspective on how future environments may be experienced. The partly divergent results of noise simulations and listening experiments therefore represent a key finding: calculated noise exposure and perceived quality capture different dimensions of the same urban configuration.

For planning, this is particularly relevant because technically effective mitigation measures may have unintended consequences for the experience of the space. By combining quantitative indicators with immersive perception-based assessment, the workflow creates a practical interface between acoustic expertise, urban design and municipal decision-making. Alternative scenarios can be tested, experienced and discussed before key spatial decisions are taken.

4.3 Limitations and future research

As a pilot investigation, the study is limited to four case study areas and six morphological variants, while the listening experiment was conducted only for the Düren case study. In larger and more complex VR scenes, differences between variants were sometimes difficult to perceive from a fixed pedestrian viewpoint, partly due to visually homogeneous façade generation and limited representation of movement through the wider area.

Future research should test the approach across broader morphologies, traffic conditions and noise sources, and examine its use in participation, design competitions, statutory planning and decision-making. Existing neighbourhoods should also be addressed, where retrofitting and incremental optimisation remain major challenges.

5. Conclusion

This paper presented an audio-visual VR framework developed within the BaLSaM project to support sound-informed decision-making in early-stage neighborhood planning. By combining urban design scenarios, traffic noise simulation, auralisation and immersive visualisation, the framework makes alternative acoustic futures perceivable and comparable before key spatial decisions are fixed.

The illustrative findings show that mesoscale urban morphology affects both calculated noise exposure and perceived acoustic quality. Building edges, block structure, height, depth and openings influence how sound propagates through neighborhoods. At the same time, the listening experiments show that acoustically effective configurations are not necessarily perceived as the most attractive environments, underlining the need to assess noise exposure and perception together.

Applied in real-world planning contexts, the framework provides an interface between acoustics, urban design and planning practice. While further validation across more sites, morphologies and noise sources is needed, the proposed workflow demonstrates how immersive audio-visual simulation can support urban soundscape design by making future acoustic environments tangible during the earliest stages of planning.

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