Form, Function and Acoustics: Productive Assets Placement and Relationship Between the Urban Soundscape Patterns and Configuration

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Abstract. Urban acoustics is influenced by several noise sources and propagation effects, a multitude of factors that make sound-based analysis a rather complex endeavor. Nevertheless, the soundscape is an important feature in cities' environments, as noise pollution affects spaces' usage and quality of life. Computational methods have been used for soundscape analysis, however a combined evaluation of the relationships between acoustics, urban form, functions and movement logics is still in demand for urban planning. This paper summarizes the different computational methods used for soundscape analysis and focuses on the use of Geographic Information Systems to construct a comparative analysis, apposing spatial information of the acoustic maps, built-structures placement and distribution, and road networks configuration, of a productive agglomerate that extends throughout the provinces of *Firenze* (Florence) and Prato. The main objective is to unearth correlations between urban design, movement dynamics and the different noise pollution classes, highlighting the soundscape patterns in the built environment, with specific reference to the distribution of productive activities. Results aim for the creation of more detailed acoustic maps, improving spatial knowledge of this productive area for urban planning purposes.

Keywords: Acoustics · Geographic information systems · Urban planning · Noise pollution

1 Introduction

Soundscape design is a paradigm shift in environmental acoustics since it incorporates spatial, social and psychological variables [1]. Understanding and defining the different forms of soundscape can assist in decision-making towards better urban reorganization and modernization [2]. In this context, several computational methods to evaluate it has been developed throughout the last decades. These methods aim to model the acoustic phenomenon, even they remain with limitations [3], as they take into account multiple parameters at once, such as road traffic [4], building attributes, and even weather conditions. The urban form and density of a defined area, also determine the ambient noise

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level [5–7]. Several parameters, such as porosity, permeability, compactness, occupation and fractal indexes, also may have a direct impact [8].

In the second half of the 20th century, the Tuscany region has seen profound landscape changes, distinguished by a shift in its agricultural environment, that shifted socioeconomic and spatial patterns from compact to scatter in some areas [9]. That, coupled with the urbanization and industrialization that were intensified during this period, shifted the urban context and had a significant effect on the region's acoustic environment, prompting constant reviews and updates of the Municipal Acoustic Classification Plans.

This paper is organized in two distinct sections, one summarizing a background of the computational methods that traditionally are used to analyze and model the urban soundscape, and a second section, that proposes an analysis apposing spatial information about the soundscape to the configuration of the foreground – built structures and background – road-circulation networks – of the urban settlements. The objective is to unearth correlations between urban design, movement dynamics and the different noise pollution classes, highlighting the soundscape patterns of the built environment. The study will focus on an important productive area in Tuscany, that comprises two provinces, which are: *Firenze* (Florence), and Prato. Results indicate a significant correlation between movement – especially in the residential and mixed-use areas – and the presence of productive activities with noise pollution.

2 Computational Urban Acoustics

Various sound field prediction methods have been established over the past few decades. According to studies, these methods can be classified into Geometrical Acoustics methods and Wave-based and diffuse methods, while others predicting analysis use Hybrid Methods [10, 11] (Fig. 1). Some reviewers also include, Acceleration and Non-graphic techniques [12].

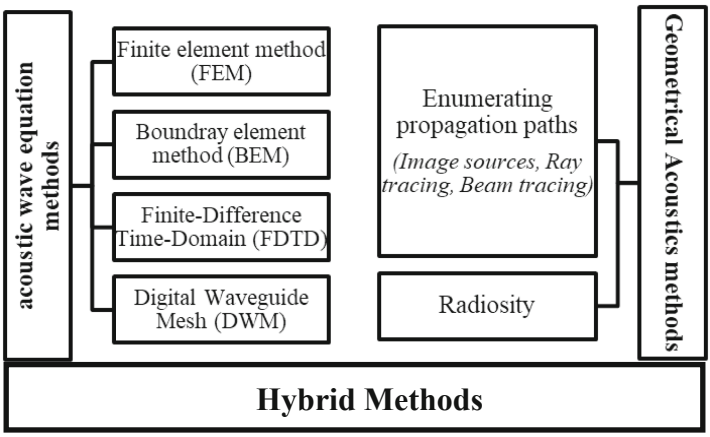

Fig. 1. Outdoor noise propagation computational methods (Source: according to [10])

It is crucial to emphasize, however, that experimental measurements are required to ensure the accuracy of digital predictions [3]. Acoustic urban analysis relies primarily on (L_{den} and L_{night}), recommended by the Environmental Noise Directive (END) [13].

Table 1 summarizes these approaches and establish a classification of past research according to their calculation methods of the environments' sound field.

Table 1. Overview of urban acoustics computational methods.

Method *(Acronym)*	Objectives	*Ref.*
Boundary element method *(BEM)*	Numerical analysis of Noise barrier using 2.5-D BEM	[14]
	Combining BEM to other methods to solve coupled vibro-acoustic problems	[15]
	Solve large acoustics problems by 3D BEM, including Fast Multipole Method	[16]
Digital waveguide mesh *(DWM)*	2-D modeling, application and limitations	[17]
	Coupled DWM-FEM for modeling wave propagation in irregularly shaped streets	[18]
Discontinuous Galerkin *(DG)*	Hybrid approach using DG-PSTD to compute arbitrary boundary conditions and complex geometries	[11]
	ExWave code based on DG method for modeling complex geometries	[19]
	DG for solving the AwRascle traffic system of hyperbolic partial differential equations	[20]
Equivalent source method *(ESM)*	2.5-D ESM for modeling an exposed and sheltered urban canyons	[21]
	Using the multi-point multipole technique, to improve the calculation's precision	[22]
	Beam tracing to analyze road traffic segmented to equivalent points	[23]
Finite-differences times-domain *(FDTD)*	Coupled FDTD-PE method for Long Range Propagation	[14]
	Comparing FDTD to TOA (observed first times of arrival) for an impulse source	[24]
	Application of 3-D Moving Window (MW-FDTD) to large-scale analysis	[25]

(*continued*)

Table 1. (*continued*)

Method *(Acronym)*	Objectives	*Ref.*
Finite element method *(FEM)*	Using FEM to predict sound propagation in buildings with a periodic distribution	[26]
	Introduction meteorological effects by Linearized Euler equation (LEE) provided by a CFD software (Open FOAM)	[14]
	Insertion loss measurements of noise barriers using FEM in 2-D	[27]
Lattice Boltzmann method *(LBM)*	Application of LBM used for incompressible flows in outdoor acoustic propagation	[28]
	Determine the numerical dissipation and dispersion resolution dependency	[29]
	LBM as a performant Bottom-up method to compute micro and macroscale algorithms	[30]
Parabolic equation *(PE)*	3-D wide angle PE to model low frequency propagation in irregular urban canyons	[31]
	Wind's speed and height effect on outdoor noise propagation	[14]
	Coupled FDTD-PE for modeling acoustic reduction through vegetation	[32]
Pseudo-spectral time-domain *(PSTD)*	Modeling scattering of a small tree geometry using PSTD	[33]
	Analysis of noise sources directivity and physical properties	[11]
	Comparing Fourier PSTD domain to DG boundaries for wave propagation in cities	[34]
*Waveguide Web *(WGW)*	Second-order accuracy in modeling sparsely reflecting outdoor acoustics	[35]

*Waveguide Web is reverberator design for outdoor, it differs from Digital Waveguide Method.

The complementarity of these numerical methods aids in the modeling of realistic acoustic scenes. The majority of these studies were conducted on the micro scale, nevertheless, few equations were developed to significantly comprehend and manage the macro scale.

3 Soundscape Environment and Geographic Information System

The use of geographic information systems (GIS) has proven its potential in various fields of applications including transportation, urban, regional planning and cartography as a key element for decision-making [36]. In the Acoustics field, early studies in 1990's

aimed to create a two-dimensional cartography in GIS, in order to develop a prototype visualization system to understand the sound behavior of different urban configurations. This requires the collection of different quantitative and qualitative information on traffic and human activities [37, 38].

Given the variety of subjects studied, these methods have progressed significantly since their inception. Several studies are attempting to model acoustic maps to locate causes of sound emission and perhaps predict future potential problems [39–42].

A significant number of studies in this field have focused on the analysis of vehicular traffic since this modal is regarded as a primary source of noise. While numerical solutions are often used to resolve the noise problem, as shown in the previous section, researchers tried to develop several plugins on GIS software for modeling the vehicle traffic according to the available data [43]. In a recent study, GIS was used as a tool to help address the parameters related to the design of buildings (type, height) that play a role in the problem of urban nuisance [44]. Bello et al., 2019 on the other hand, used a GIS software called "URBANE" for 3-D visualization after developing an innovative noise-detecting device that combines learning machines and human interactions in New York City's neighborhoods [45]. With these studies in consideration, in the last years, GIS-based sound analyses have become reliable in apposing infrastructural data to the soundscape, yet some aspects about configuration still merit further exploration.

4 Methodology

This investigation aims to analyze the soundscape and spatial forms using an Opensource GIS Software – QGIS [46]. A preliminary step consists of geometry preparation after delimiting our study area which comprises six municipalities in the provinces of *Firenze* and *Prato.* These areas form a continuous productive area that comprises the largest industrial agglomeration in Tuscany. Infrastructural data comprises the built-structures, derived from the Tuscany Region Built-Structure's dataset *(Edificato 2k,10k 1988–2013*) [47], and the road-circulation network, obtained from the Tuscany Region Road Graph (*Grafo Itnet)* [48]. In order to understand the urban structure and movement dynamics among the elements that make up the studied area, the sectioned graph was modeled using the Space Syntax's Angular Analysis [49] measures of Normalized Angular Integration (NAIN) and Normalized Angular Choice (NACH) which possess a good correspondence regarding vehicular traffic and movement potentials – both regarding accessibility – NAIN; and preferential routes within the System - NACH [50, 51]. For the acoustic analysis, the Municipal Acoustic Classification Plans *(Piani Comunali di Classificazione Acustica - PCCA*) for the Tuscany Region, established on December 5, 2012. These plans specify six acoustic groups that are recommended by the Environmental Noise Directive (END [52] and were used to determine the limits in noise pollution for each area. With the road-circulation network modeled it is possible to focus on the complex relationship between the studied area's forms and functions of the background and foreground, and the acoustic environment, through the correlation between the acoustic classes, roads that present a greater degree of movement potential and buildings typologies.

5 Results and Discussion

The research area encompasses six municipalities, distributed in-between the *Firenze* and *Prato* provinces: *Calenzano, Campi Bisenzio, Firenze, Sesto Fiorentino and Signa*, that are part of the metropolitan city of *Firenze*, while *Prato* is the capital city of its homonymous province (Fig. 2). This region covers an area of 373.34 Km^2 and is well-known for its appeal as a touristic destination. Still, this territorial extent also possesses a substantial importance within Tuscany as a productive and industrialized area [9].

From an urban morphology standpoint, it is possible to observe that the analysis area, is rather compact in form, exhibiting a distinguishable conurbation that extends across the six municipalities (Fig. 3). The area locates the largest concentration of industrial-dedicated buildings and industrial land use within the region, with those productive spaces being characterized by the orthogonal-based configuration of its road-circulation network. Residential presence is also extensive throughout the area, with a cohesive distribution. The road-infrastructure in the boundary areas, especially around the municipalities of *Calenzano* and *Sesto Fiorentino* exhibit, instead, a radicle-based organization, around the main roadway, and have a productive land-use mainly dedicated to agricultural production, or as natural protected areas (Fig. 3).

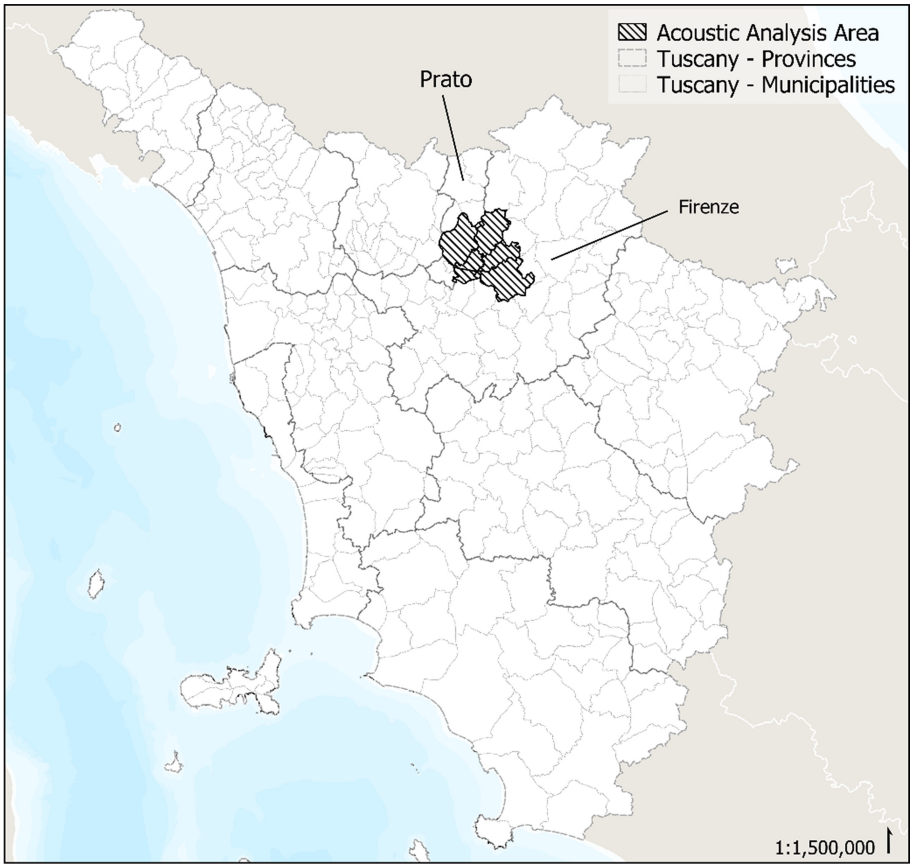

Fig. 2. Delimitation of the case study area, within the Tuscany region.

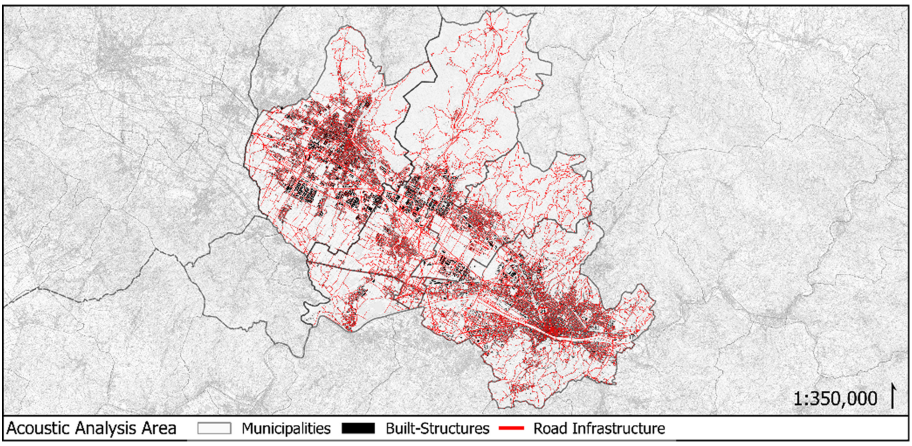

Fig. 3. Delimitation of the case study area, with the disposition of municipalities, built-structures and road-infrastructure.

The acoustic data from the PCCA specifies six acoustic groups (I - lowest, II, III, IV, V, VI - highest) which range from 50 to 70 decibels, which an increase of 5 decibels in-between ranges, and are allocated to different areas of the territory (Fig. 4). The soundscapes of *Firenze* and *Prato* provinces were analyzed using a soundwalk process, with the aim of improving and changing existing soundscapes while taking user feedback into account.

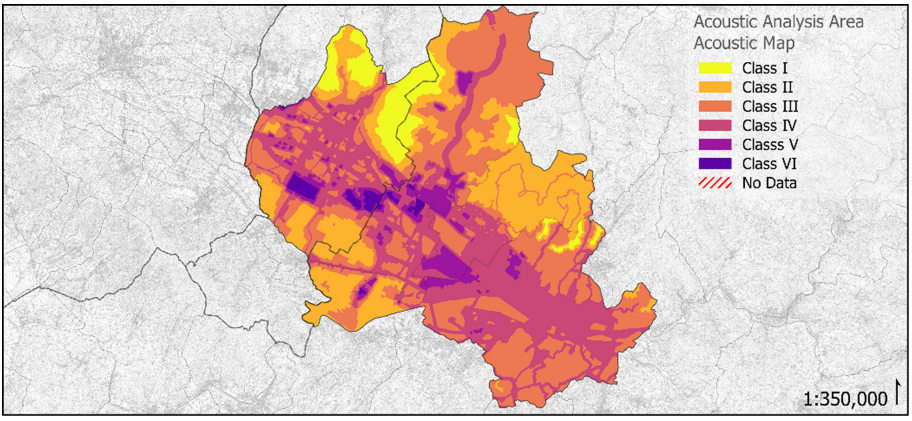

Fig. 4. Delimitation of acoustic map, highlighting the noise pollution classes

The study found a strong link between soundscape perception and measurements, noise sources, and perceived landscape quality [53]. It can be observed that the conurbation extension possesses values that range class III to class VI, albeit some areas around the city centers, especially in *Firenze* and *Prato*, have a class II classification, which is

the minimal for both urbanized and rural areas. Class I is only found in the mountain area in-between *Calenzano* and *Prato*, a non-urbanized site (Fig. 4).

It can be noticed that the areas with compact urban fabric have higher noise characters, due to the intensity of human activities in the area – predominantly made of residential and mixed-uses, that are categorized mostly in the classes III and IV (Fig. 5).

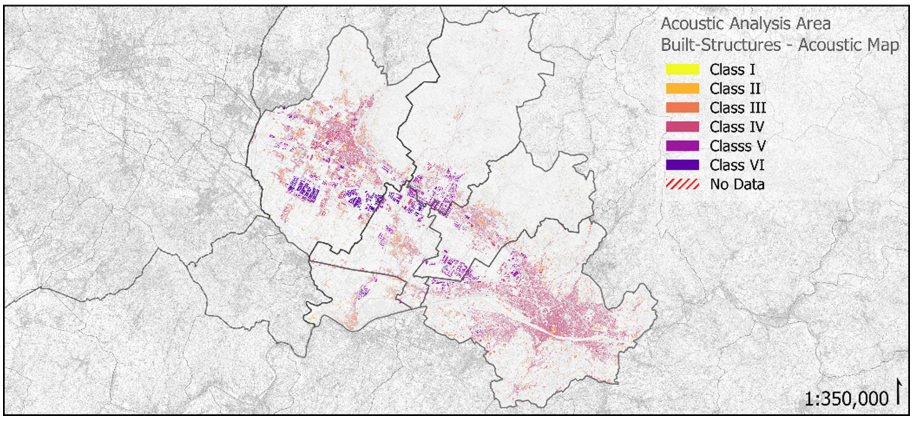

Fig. 5. Built-structures apposition with the acoustic map noise classes.

Industrial-dedicated areas, however, are included in the classes V and VI. These sites are predominant on *Prato*, that locates most of the areas categorized under the highest class (VI). In that aspect, it is highlighted that only the municipalities *Prato, Calenzano, Campi Bizenzio* and *Signa* possess buildings included in the highest class (VI), while buildings categorized under in the class V are present in all municipalities. Few small and isolated rural estates are included in the class I, placed in-between *Calezano* and *Prato* (Fig. 5).

The percentual distribution of the built-structures located within each sound character class is depicted in Table 2, while the Fig. 6 establishes the relation between the soundscape classes and the urban functions – allocating the number of buildings that have a determined urban function within each acoustic category.

Table 2. Percentual distribution of built-structures according to the acoustic classes

Class I	Class II	Class III	Class IV	Class V	Class VI
0.1%	3%	27.3%	65.1%	3.8%	0.6%

Residential buildings represent the main bulk of the noise sources with a high rate of 25.8% registered in class III and 70.6% registered in Class IV. Albeit their little impact on daily sound quality, rural and unidentified areas remain an important source too, accounting for 37.5% and 70.6 if Class III and IV, respectively. Industrial buildings also

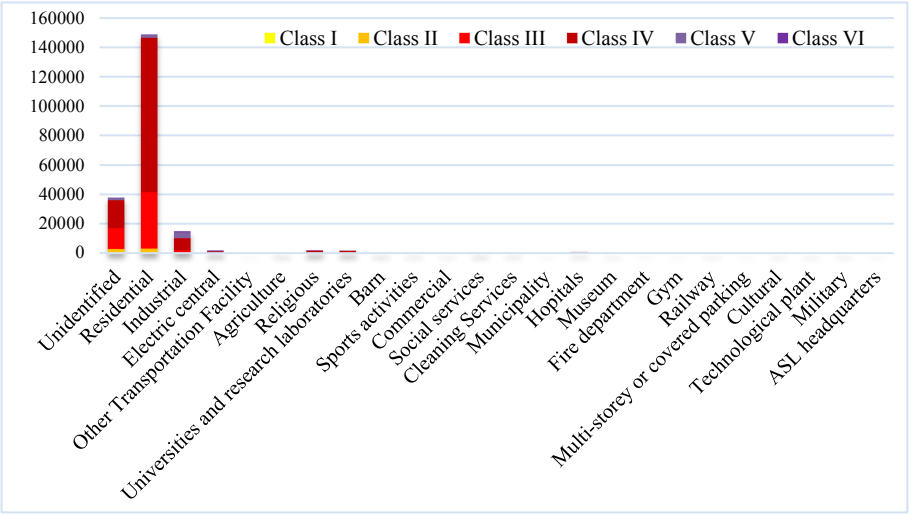

Fig. 6. Relationship between noise classes and built structures.

have a significant effect in the sound context. The bulk of these factories are based in the municipalities of Prato, Calenzano, Signa – with sources arriving at the VI class, and in a lesser degree, Sesto Fiorentino and Firenze. Industrial buildings are disposed as follows: 54.7% in the class IV and 27.1% in the class V. Other activities, such as cultural and military functions, are characterized by a medium-low-noisy environment (Class III) and, due to their limited presence contribute less to the overall acoustic landscape. Hospitals tend to be located within areas within Class II.

The road-circulation network in the study area is dense and structured in a conurbation, where the main connection in-between the municipalities is made through urban highways (Fig. 7) These structures are listed on the classes IV and V, meaning that vehicular traffic represents the main noise source within the region, and has a direct impact on the daily life of residents and on their health.

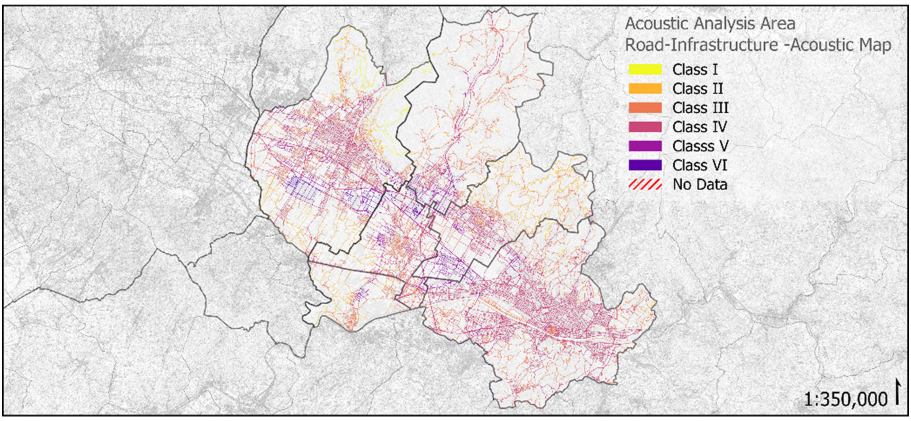

Fig. 7. Road-circulation network apposition to the acoustic map noise classes

The Angular Segment Analysis shows an aggregated urban fabric, where Normalized Angular Integration (NAIN) measures were calculated independently for each one of the six municipalities and apposed to compose the whole system (Fig. 8a). In this aspect it is possible to highlight the local centers for each municipality, as well as have an idea of where the interactions between local and global road-circulation networks occur. These are depicted when NAIN values are restricted to their highest values – 90° and 100° deciles (Fig. 8b) – that represent the centrality cores of each urban settlement, or the places with the highest accessibility. When observed alongside the Normalized Angular Choice (NACH), calculated at global scale for the whole system, and establish the internal hierarchies regarding the preferential routes within the system (Fig. 8a). As observed in previous studies, betweenness centralities (the mathematical component of NACH) possess a homothetic behavior [54], which justify its modeling as a whole region, unlike the integration that varies according to depth.

Through the restriction of the global NACH - 90° and 100° deciles – it is possible assess the road-segments that structure the paths across the region and establish the linkages among the Integration cores (Fig. 9b).

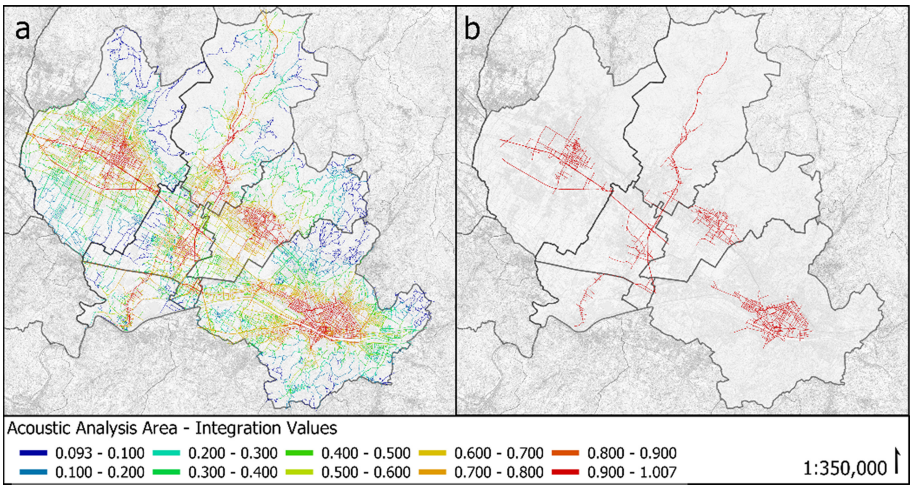

Fig. 8. Normalized Angular Integration (NAIN) values for each municipality (a) and Integration Cores restricted to the 90° and 100° deciles (b).

Angular Analysis models (NAIN and NACH), where then correlated to the noise classes, in order to highlight if movement potentials – that are a representation of the expected movement, had a correspondence with the degree of noise identified in each space (Fig. 10).

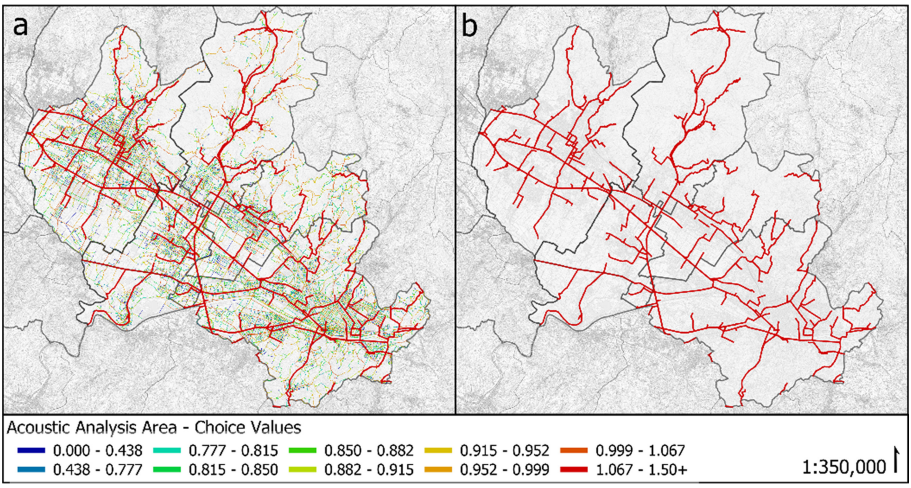

Fig. 9. Normalized Angular Integration (NACH) values for the region-wide system (a) and *Preferential Routes* restricted to the 90° and 100° deciles (b).

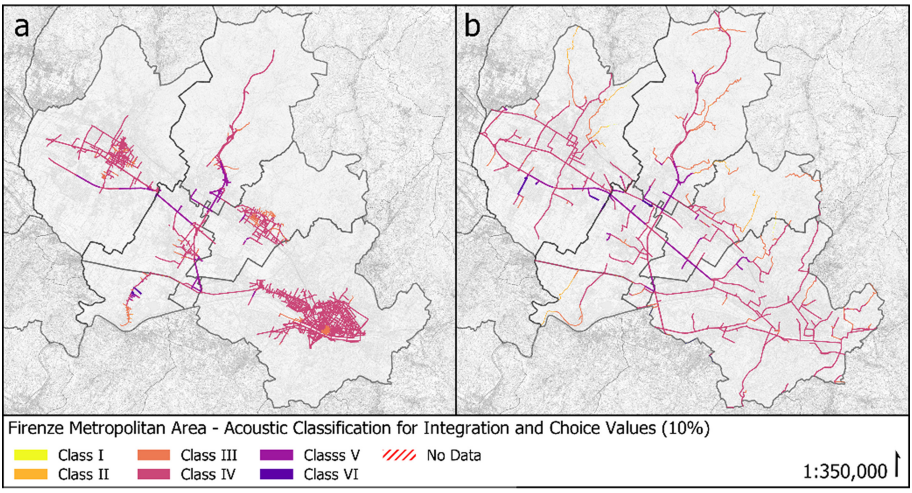

Fig. 10. Acoustic classification and correlation for normalized angular integration (NAIN) and normalized angular choice (NACH) values (90° and 100° deciles)

Correlations demonstrate that 85.61% of the road-elements within highest NAIN values (integration cores) belongs to class IV, whereas 66.98% of the most sought *preferential routes* (NACH) is included in this same class, which demonstrate a significative relation between movement and noise levels. It is important to highlight that class V and VI are mostly restricted to the industrial areas (Fig. 11).

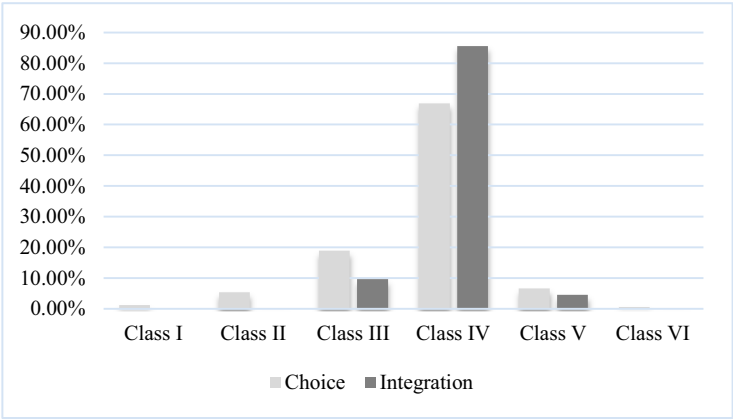

Fig. 11. Restricted normalized angular integration (NAIN) and normalized angular choice (NACH) – 90° and 100° deciles – distribution in relation to acoustic classes.

Road-elements in the Classes I and II are restricted to the *preferential routes*, given that these extend towards the municipalities' borders, where the suburban condition reflects a lower noise level. Classes III, IV and V have a better distribution regarding the number of road elements: while Class III has a predominance of *preferential routes*, Integration has a predominance on Class IV, explained, as the most road-elements are located within central urban areas – especially in *Firenze*, which has a considerable tourism activity, thus, pedestrian movement, in its historical center. Class V, in the other hand, presents an equilibrium between Integration and Choice, and mostly indicates that the industrial activities are integrated within the system, as well as placed near the preferential routes. Being Class IV the dominant noise class in the urban system it explains the assumed relationship between the movement and noise levels.

6 Conclusions

Results showed considerable impact of the form function and spatial configuration on the acoustic environment. It is highlighted that vehicular traffic and the concentration of pedestrians, motivated by tourism and commercial activities are the main source of noise pollution in Firenze city center. In the other parts of its metropolitan area, however, while vehicular movement still contributes to the acoustic environment, productive activities – mainly industrial – are the main sources of noise pollution in the region, with the higher classes being mostly concentrated at the city of Prato. Highest values of global measures of the Angular Segment Analysis have the ability to provide a clear overview of the acoustic phenomenon.

The relation between road-circulation network configuration – movement potentials, the background; and the built-structures – the foreground can serve as a helpful planning instrument for updating the Municipal Acoustic Classification Plan, since it introduces variables that can produce a finer detail regarding the noise sources and their distribution.

References

1. Kang, J.: From understanding to designing soundscapes. Front. Archit. Civ. Eng. China **4**, 403–417 (2010)
2. Raimbault, M., Dubois, D.: Urban soundscapes: experiences and knowledge. Cities **22**, 339–350 (2005)
3. Hornikx, M.T.: questions concerning computational urban acoustics. Build. Environ. (2016). https://doi.org/10.1016/j.buildenv.2016.06.028
4. Khan, J., Ketzel, M., Kakosimos, K., Sørensen, M., Jensen, S.S.: Road traffic air and noise pollution exposure assessment – a review of tools and techniques. Sci. Total Environ. **634**, 661–676 (2018)
5. Guedes, I.C.M., Bertoli, S.R., Zannin, P.H.T.: Influence of urban shapes on environmental noise: a case study in Aracaju - Brazil. Sci. Total Environ. **412–413**, 66–76 (2011)
6. Salomons, E.M., Berghauser Pont, M.: Urban traffic noise and the relation to urban density, form, and traffic elasticity. Landscape Urban Plann. **108**, 2–16 (2012)
7. Tang, U.W., Wang, Z.S.: Influences of urban forms on traffic-induced noise and air pollution: results from a modelling system. Environ. Model. Softw. **22**, 1750–1764 (2007)
8. Oliveira, M.F., Silva, L.T.: How urban noise can be influenced by the urban form. 6th WSEAS International Conference on Cellular and Molecular Biology, Biophysics and Bioengineering, BIO 2010, 8th WSEAS International Conference on Environmental Ecosystems and Development, EED 2010, International Conference on Biosciences and Bioinformatics, ICBB 2010 I, pp. 31–36 (2010)
9. Zullo, F., Paolinelli, G., Valentina, F., Fiorini, L., Romano, B.: Urban development in Tuscany. Land uptake and landscapes changes. TeMA J. Land Use Mob. Environ. **8**, 183–202 (2015)
10. Lakka, E., Malamos, A., Pavlakis, K.G., Ware, J.A.: Spatial sound rendering – a Survey. Int. J. Interact. Multimedia Artif. Intell. **5**, 33 (2018)
11. Georgiou, F., Munoz, R.P., Rietdijk, F., Zachos, G.: Prediction and auralisation of urban sound environments. In: Urban Sound Planning - the Sonorus project 118 (DanagardLiTHO, 2016)
12. Charalampous, P., Michael, D.: Sound propagation in 3D spaces using computer graphics techniques. In: Proceedings of the 2014 International Conference on Virtual Systems and Multimedia, VSMM 2014, pp. 43–49 (2014) https://doi.org/10.1109/VSMM.2014.7136674
13. European Parliament and Council of the European Union. Assessment and management of environmental noise (EU Directive). Official J. Eur. Commun. (2002). http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32002L0049&from=EN%5Cn, http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32002L0049. https://doi.org/10.1016/j.jclepro.2010.02.014
14. Toyoda, M. et al. Noise propagation Simulation. In: Sakuma T., Sakamoto S., Otsuru T. (eds.) Computational Simulation in Architectural and Environmental Acoustics, pp. 179–242. Springer, Tokyo (2014). https://doi.org/10.1007/978-4-431-54454-8
15. Kirkup, S.: The boundary element method in acoustics: a survey. Appl. Sci. **9**, 48 (2019)
16. Bashir, I., Carley, M.: Development of 3D boundary element method for the simulation of acoustic metamaterials/metasurfaces in mean flow for aerospace applications. Int. J. Aeroacoustics **19**, 324–346 (2020)
17. Murphy, D., Kolloniemi, A., Mullen, J., Shelley, S.: Acoustic modeling using the digital waveguide mesh. IEEE Signal Process. Mag. **24**, 55–66 (2007)
18. Pelat, A., Felix, S., Pagneux, V.: A coupled modal-finite element method for the wave propagation modeling in irregular open waveguides. J. Acoust. Soc. Am. **129**, 1240–1249 (2011)
19. Schoeder, S., Wall, W.A., Kronbichler, M.: ExWave: a high performance discontinuous galerkin solver for the acoustic wave equation. SoftwareX **9**, 49–54 (2019)

20. Buli, J., Xing, Y.: A discontinuous galerkin method for the aw-rascle traffic flow model on networks. J. Comput. Phys. **406**, 109183 (2020)
21. Hornikx, M., Forssén, J.: The 2.5-dimensional equivalent sources method for directly exposed and shielded urban canyons. J. Acoust. Soc. Am. **122**, 2532 (2007)
22. Gounot, Y.J.R., Musafir, R.E.: Simulation of scattered fields: some guidelines for the equivalent source method. J. Sound Vib. **330**, 3698–3709 (2011)
23. Wang, H., Cai, M., Cui, H.: Simulation and analysis of road traffic noise among urban buildings using spatial subdivision-based beam tracing method. Int. J. Environ. Res. Public Health **16**(14), 2491 (2019)
24. Cheinet, S., Ehrhardt, L., Broglin, T.: Impulse source localization in an urban environment: time reversal versus time matching. Acoust. Soc. Am. **139**, 128–140 (2016)
25. Oikawa, T., Sonoda, J., Honma, N., Sato, M.: Analysis of lighting electromagnetic field on numerical terrain and urban model using three-dimensional MW-FDTD parallel computation. Electron. Commun. Japan **100**, 76–82 (2017)
26. Molerón, M., Félix, S., Pagneux, V., Richoux, O.: Sound propagation in periodic urban areas. J. Appl. Phys. **111**, 114906 (2012)
27. Papadakis, N.M., Stavroulakis, G.E.: Finite element method for the estimation of insertion loss of noise barriers: comparison with various formulae (2D). Urban Sci. **4**, 77 (2020)
28. Fraser, N., Hall, R.: Simulating acoustic propagation using a lattice boltzmann model of incompressible fluid flow, pp. 42–47 (2006)
29. Viggen, E.M.: The lattice Boltzmann method with applications in acoustics. Master's thesis, Norwegian University of Science, pp. 1–5 (2009)
30. Brès, G.A., Pérot, F., Freed, D.: Properties of the Lattice-Boltzmann method for acoustics. In: 15th AIAA/CEAS Aeroacoustics Conference (30th AIAA Aeroacoustics Conference), pp. 11–13 (2009). https://doi.org/10.2514/6.2009-3395
31. Doc, J.-B., Lihoreau, B., Félix, S., Faure, C., Dubois, G.: Three-dimensional parabolic equation model for low frequency sound propagation in irregular urban canyons. J. Acoust. Soc. Am. **137**, 310–320 (2015)
32. Ow, L.F., Ghosh, S.: Urban cities and road traffic noise: reduction through vegetation. Appl. Acoust. **120**, 15–20 (2017)
33. van Renterghem, T., Botteldooren, D., Verheyen, K.: Road traffic noise shielding by vegetation belts of limited depth. J. Sound Vib. **331**, 2404–2425 (2012)
34. Muñoz, R.P., Hornikx, M.: Hybrid fourier pseudospectral/discontinuous galerkin time-domain method for wave propagation. J. Comput. Phy. **348**, 416–432 (2017). https://doi.org/10.1016/j.jcp.2017.07.046
35. Stevens, F., Murphy, D.T., Savioja, L., Valimaki, V.: Modeling sparsely reflecting outdoor acoustic scenes using the waveguide web. IEEE/ACM Trans. Audio Speech Lang. Process. **25**, 1566–1578 (2017)
36. Malczewski, J.: GIS-based multicriteria decision analysis: a survey of the literature. Int. J. Geogr. Inf. Sci. **20**, 703–726 (2006)
37. Servigne, S., Laurini, R., Kang, M.-A., Li, K.J.: First specifications of an information system for urban soundscape. In: Proceedings IEEE International Conference on Multimedia Computing and Systems, vol. 2, pp. 262–266 (1999)
38. Krygier, J.B.: Sound and geographic visualization. In: Modern Cartography Series, vol. 2 (Elsevier Science Ltd, 1994)
39. Zannin, P.H.T., de Sant'Ana, D.Q.: Noise mapping at different stages of a freeway redevelopment project - A case study in Brazil. Appl. Acoust. **72**, 479–486 (2011)
40. Hossam Eldien, H.: Noise mapping in urban environments: application at Suez city center. In: 2009 International Conference on Computers and Industrial Engineering, CIE 2009, pp. 1722–1727 (2009). https://doi.org/10.1109/iccie.2009.5223696

41. Bilaşco, Ş, Govor, C., Roşca, S., Vescan, I., Filip, S., Fodorean, I.: GIS model for identifying urban areas vulnerable to noise pollution: case study. Front. Earth Sci. **11**(2), 214–228 (2017). https://doi.org/10.1007/s11707-017-0615-6
42. Garcia, J.S., et al.: Spatial statistical analysis of urban noise data from a WASN gathered by an IoT system: application to a small city. Appl. Sci. (Switzerland) **6**(12), 380 (2016)
43. Cai, M., Zou, J., Xie, J., Ma, X.: Road traffic noise mapping in Guangzhou using GIS and GPS. Appl. Acoust. **87**, 94–102 (2015)
44. Huang, B., Pan, Z., Liu, Z., Hou, G., Yang, H.: Acoustic amenity analysis for high-rise building along urban expressway: modeling traffic noise vertical propagation using neural networks. Transp. Res. Part D **53**, 63–77 (2017)
45. Bello, J.P., et al.: Sonyc. Commun. ACM **62**, 68–77 (2019)
46. QGIS, Hannover, version 3.16 (2020). http://www.qgis.org/en/site/index.html
47. Regione Toscana, Direzione Urbanistica e Politiche Abitative - Sistema Informativo Territoriale e Ambientale – SITA.: Edificato 2k, 10k 1988–2013. (2019b). http://www.502.regione.toscana.it/geoscopio/cartoteca.html
48. Toscana, R.: (2019b) Direzione Urbanistica e Politiche Abitative - Sistema Informativo Territoriale e Ambientale – SITA.: Grafo stradario e ferroviario della Regione Toscana - Itnet. http://www.502.regione.toscana.it/geoscopio/cartoteca.html
49. Turner, A.: Angular Analysis. In: Proceedings of the 3rd International Symposium on Space S*yntax,* pp. 7–11. Georgia Institute of Technology, Atlanta, Georgia (2001)
50. Turner, A.: From axial to road-centre lines: a new representation for space syntax and a new model of route choice for transport network analysis. Environ. Plann. B. Plann. Des. **34**, 539–555 (2007)
51. Hillier, B., Yang, T., Turner, A.: Normalising least angle choice in depthmap - and how it opens up new perspectives on the global and local analysis of city space. J. Space Synt. **3**(2), 155–193 (2012)
52. Toscana, R.: Direzione Urbanistica e Politiche Abitative - Sistema Informativo Territoriale e Ambientale – SITA.: Piano Comunale di Classificazione Acustica - PCCA; art 4 l.r. 89/98 - http://www.502.regione.toscana.it/geoscopio/cartoteca.html(2019c)
53. Luzzi, S., Bartalucci, C., Radicchi, A., Brusci, L., Brambilla, G. Participative soundscape projects in Italian contexts. In: Inter-Noise 2019 MADRID - 48th International Congress and Exhibition on Noise Control Engineering (2019)
54. Altafini, D., Cutini, V.: Homothetic behavior of betweenness centralities: a multiscale alternative approach to relate cities and large regional structures. Sustainability **12**(19), 7925 (2020). https://doi.org/10.3390/su12197925