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How Can Urban Forms Balance Solar and Noise Exposition for a Sustainable Design?

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Abstract: Sustainable development requires efficient planning and management of both natural and built resources. The identification of urban forms that best balance exposure to solar radiation and urban noise, ensuring compliance with residential construction regulations and European directives may be carried out through simulations. The proposed methodology involves simulating various scenarios and adjusting parameters of selected urban forms to evaluate the availability of solar radiation and the noise exposure on building façades within a specific context. In addressing the requirements for solar and noise optimization, predictive models (solar and noise) were employed, utilizing urban form indicators to relate these three variables. The case study demonstrates the inverse behavior of these variables in relation to the same urban forms. The findings highlight the optimal urban forms for each scenario. The enclosed form was identified as the most suitable for minimizing noise exposure, while the linear form is optimal for maximizing solar radiation exposure. This approach allows the designer to make informed decisions that balance these competing requirements, achieving a compromise between optimizing thermal and acoustic performance. The ultimate goal is to enhance the overall comfort of the building, reduce energy consumption, and promote a sustainable building solution.

Keywords: urban form; solar radiation; urban noise

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1. Introduction

The pursuit of sustainable development in urban environments demands a careful balance between energy efficiency and environmental quality. In this context, urban morphology plays a crucial role in determining building performance and occupant well-being. Among the many environmental factors that affect urban living, solar radiation and urban noise stand out for their direct impact on thermal and acoustic comfort. Adequately managing both variables has become increasingly important, especially in light of growing environmental concerns and the tightening of European construction regulations.

Solar radiation is essential for passive heating, natural lighting, and the reduction in energy consumption in buildings. Conversely, excessive exposure to urban noise is associated with a range of adverse effects on human health and quality of life. Urban form—the spatial arrangement, geometry, and structure of built environments—significantly influences both these variables. However, while numerous studies have examined the relationship between urban form and either solar access or noise propagation independently, few have considered their interaction simultaneously.

Addressing these issues in an integrated manner is essential for guiding urban design decisions that foster sustainability. This study explores the dual challenge of optimizing urban form for both solar radiation and noise reduction. Through a simulation-based methodology, this research evaluates multiple urban form scenarios by adjusting key morphological parameters. Using predictive models and urban form indicators, it investigates how these variables behave and interact, identifying configurations that offer the best correlation.

The study reveals an inverse relationship between optimal conditions for solar and noise performance, highlighting the need for compromise and hybrid design strategies. This integrated approach contributes to a more informed urban planning process, supporting the development of built environments that promote energy efficiency, acoustic comfort, and regulatory compliance.

2. Literature Review

Recent studies highlight the interaction between urban form and noise, pointing out that elements, such as building height, street width and façade irregularities, influence noise distribution. Acoustic mapping and modeling are useful tools for visualizing and planning suitable urban noise environments. The influence of urban geometry on thermal comfort and solar radiation is also significant, while new studies explore emerging techniques to mitigate environmental noise in urban environments.

2.1. The Importance of Urban Form in a City's Sustainability

The role of urban form in achieving sustainable development has been increasingly acknowledged in recent decades. Since the late 20th century, many countries have implemented urban form policies as part of their environmental planning efforts [1], recognizing how urban form influences the sustainability of cities. Alawadi [2] notes that the question of identifying the 'optimal' urban form for sustainable environments has long been a subject of inquiry.

Urban form is characterized by the relationship between the built environment and surrounding open spaces within a given landscape. It encompasses the connections and interactions between various layers and systems, whether built or unbuilt, and their integration with other elements of the urban context, such as location, topography, and solar exposure [3].

The impact of urban form (or built-up mass) on the composition of urban landscapes is closely tied to the morphological characteristics of the built environment. This includes the typology of buildings, patterns of aggregation, building configurations, modes of access, and the definition of external spaces between structures [4,5]. Urban form can therefore be understood as a combination of elements that form the urban layout and its intrinsic characteristics [6].

As highlighted by Bibri [7], contemporary discussions on the sustainability of urban planning continue to address the challenges posed by the rapid evolution of urban forms and the unsustainability of existing ones. These debates emphasize the importance of integrating environmental, economic, and social considerations and exploring how the built environment, through its form, can reduce long-term energy inefficiencies [7].

Macke, Rubim Sarate, and de Atayde Moschen [8] argue that cities can be sustainable without relying solely on technological intelligence. While smart technologies can be deployed independently of sustainable development principles [9–12], the integration of both concepts has given rise to the notion of the smart sustainable city [13–18]. The concept is: the more information available, the smarter the decision [19–21].

As the range of variables considered increases, unintended consequences of decisions can be minimized. However, decision making is always context dependent, influenced by factors, such as geography, economics, and time [22]. Urban planning, shaped by predefined premises and processes, often involves a degree of uncertainty and projection for future outcomes [23].

Urban policy conceptualizes smart urban development as a transformative process aimed at achieving sustainability [13,18,24]. This approach places decisions at the core of design and planning processes, advocating for the use of smart indicators or automated decision-making assumptions. These assumptions must address economic, social, and environmental challenges, with a particular focus on mobility and the optimization of urban form [13,19,25].

The conceptual goals of sustainability involve fostering smart habits, monitoring decision-making processes, and guiding the development of sustainable (smart) urban forms and cities [26]. These objectives align with global frameworks, such as the Sustainable Development Goals (SDGs) [27,28].

The concept of a sustainable city is often associated with technical outcomes [29], urban efficiency [30], or broader sustainability impacts [10,11,31–33].

To achieve environmentally sustainable performance, dense and functionally diverse urban plans require an integrated design approach that incorporates sustainable services and technologies [34]. Similarly, policy planning must address the development of smart and sustainable cities [8].

However, the effectiveness of such proposals can be constrained by political and legislative frameworks. Decision-making processes may sometimes proceed without ensuring that the chosen solutions represent the best technical options [29]. A lack of integration across systems, including legal frameworks, can introduce inconsistencies—either through excess or omission—that hinder the optimization of solutions, particularly those aimed at reducing energy consumption or enhancing urban sustainability.

A smart sustainable city, as defined in alignment with the Brundtland Report [35], is one that addresses the needs of its current inhabitants while safeguarding the ability of future generations to meet their own needs. This balance is achieved through the integration of advanced Information and Communication Technologies (ICT) [11,36].

The notion of a sustainable city is inherently complex and open to interpretation [18,25,37]. Although the concept is challenging to define and expand upon, its primary goals are explicit, focusing on the adoption of environmentally friendly policies and regenerative strategies designed to reduce adverse impacts on the environment [9,38,39].

2.2. The Relationship Between Urban Form and Exposure to Noise

Research exploring the relationship between urban form and noise exposure has gained momentum only recently. Villaverde, Hornero, and Ravé [40] examined the connection between noise levels and urban geometries, such as building height and street width (H/W ratio). Similarly, other studies have demonstrated that urban geometry significantly affects noise distribution patterns [41,42].

Several investigations have delved into the effects of façade irregularities on street noise diffusion [43–46]. Heutschi [47] developed reference tables to estimate the impact of urban canyon configurations, such as façade height, street width, façade absorption coefficients, and surface diffusion, on traffic noise levels in straight streets.

The design of buildings and roofing has been extensively studied for their impact on façades not directly exposed to noise. Research has shown the importance of such factors in creating quieter façades within urban environments [48–52]. (For example, Van Renterghem and Botteldooren [51] highlighted how various roofing designs can influence sound propagation, offering strategies to mitigate noise through architectural interventions).

The physical attributes of urban form, such as building density, open spaces, and the spatial arrangement of buildings, also play a key role in determining environmental noise levels [5,53].

Acoustic mapping and noise prediction tools have been identified as effective in assessing environmental noise. These methods facilitate noise quantification and visualization, contributing to improved urban noise management [54–56].

While the literature on the relationship between urban geometry and traffic noise is limited [57], recent studies integrate advanced techniques, such as noise simulation and modeling, to better understand and mitigate noise propagation within urban environments [4,5,41].

Magrini and Lisot [58] proposed a model to evaluate the effects of building configurations on noise reduction for façades. Meanwhile, Souza and Giunta [59] investigated the correlation between urban noise and the Floor Space Index (FSI) using an Artificial Neural Network model, showcasing the potential of computational approaches in urban noise studies. Beyond noise, urban geometry also influences thermal comfort [60] and solar radiation distribution [61], highlighting its broader environmental significance.

2.3. The Relationship Between Urban Form and Exposure to Solar Radiation

In a current urban context, Vartholomaios [62] considers the relationship between form, climate and (residential) energy consumption to be a vague topic for many planning and design professionals, despite its pertinence.

In their literature reviews, Ko [63] and Vartholomaios [64] consider two different approaches to energy-efficient urban design strategies. The first points to the need to reduce heating loads by maximizing the passive use of the sun, where urban forms are characterized by southern orientations or minimum distances [65–67]. The other strand points to the use of compact urban blocks, such as those in historic European centers, where urban densities are higher and minimize undesirable heat loss or gain [68–70].

According to Vartholomaios [64], these strategies could previously have been considered incompatible, but he believes that more recent studies [66,71–73] have shown that the development of compact urban forms with high passive solar potential is feasible.

Although the correlation between urban form and energy use is multifaceted, recognized and emphasized in design manuals [65], there are few published studies correlating urban form and energy use [63].

There are several studies that parameterize specific environmental factors, such as street and building design [74], urban density [73], or through algorithms [75]; however, they do not quantify the energy used and its impact [64,76].

In the same vein, the parameterization of studies tends to focus on the particularities of geometry, usually in the form of a matrix of buildings [71,76], 'urban canyons' [64,73,74] or urban blocks [75,77].

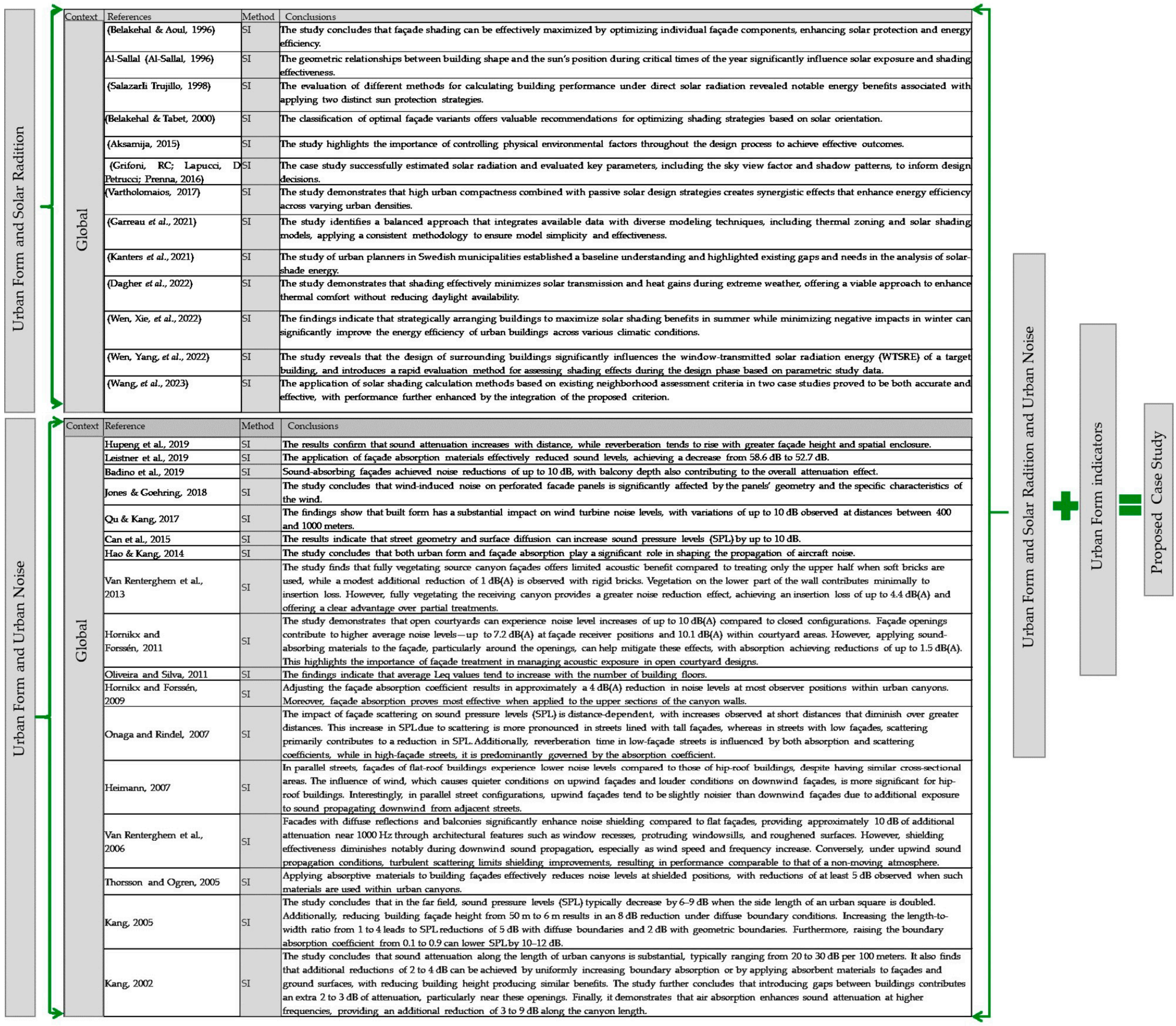
There are also studies comparing the energy performance of blocks with other urban typologies, albeit rare and generally not considering the effect of changes in important morphological parameters, such as orientation [69], street width [78] or urban block form [79], in relation to energy consumption.

However, the effect of urban geometry and solar orientation and shading conditions for different latitudes has been studied by researchers [80–83], while other studies have correlated solar access, solar orientation with urban density, orientation and solar access issues in an attempt to investigate urban design options [72,84–87].

According to Vartholomaios [62], the existing literature regarding the relationship between urban form and residential energy use leaves open or partially answers some questions regarding the performance of the urban block in relation to other typologies. In particular, can a given urban form achieve low energy consumption while using geometric, morphological and measurable approaches? What characteristics should urban forms have and what should they have in common in terms of geometry and urban density in order to be comparable and measurable? Could there be a specific urban typology that is favored over the others?

3. Methodology

The aim of this research was to study the influence of urban form both on solar radiation gains in the vertical envelope of the building and on the noise exposure that reaches the façades of the selected urban forms. The methodological foundation of this study is grounded in the analysis of case studies that examine the relationship between urban form and urban noise and urban form and solar radiation. Particular emphasis is placed on studies that rely on simulation-based approaches developed from theoretical models, without the use of field measurements or laboratory data. Despite the absence of empirical input, these studies yield credible findings and meaningful conclusions. The validity of the present research is similarly rooted in a theoretical model that reflects the characteristics of Portuguese urban architecture. Figure 1 highlights several relevant case studies that utilize simulation as their primary methodological tool to explore these relationships, alongside an outline of the methodological approach adopted in this article.



Context	References	Method	Conclusions
Global	(Belakehal & Aoul, 1996)	SI	The study concludes that façade shading can be effectively maximized by optimizing individual façade components, enhancing solar protection and energy efficiency.
	Al-Sallal (Al-Sallal, 1996)	SI	The geometric relationships between building shape and the sun's position during critical times of the year significantly influence solar exposure and shading effectiveness.
	(Salazarli Trujillo, 1998)	SI	The evaluation of different methods for calculating building performance under direct solar radiation revealed notable energy benefits associated with applying two distinct sun protection strategies.
	(Belakehal & Tabet, 2000)	SI	The classification of optimal façade variants offers valuable recommendations for optimizing shading strategies based on solar orientation.
	(Aksamija, 2015)	SI	The study highlights the importance of controlling physical environmental factors throughout the design process to achieve effective outcomes.
	(Grifoni, RC; Lapucci, D Petrucci; Prenna, 2016)	SI	The case study successfully estimated solar radiation and evaluated key parameters, including the sky view factor and shadow patterns, to inform design decisions.
	(Vartholomaios, 2017)	SI	The study demonstrates that high urban compactness combined with passive solar design strategies creates synergistic effects that enhance energy efficiency across varying urban densities.
	(Garreau *et al.*, 2021)	SI	The study identifies a balanced approach that integrates available data with diverse modeling techniques, including thermal zoning and solar shading models, applying a consistent methodology to ensure model simplicity and effectiveness.
	(Kanters *et al.*, 2021)	SI	The study of urban planners in Swedish municipalities established a baseline understanding and highlighted existing gaps and needs in the analysis of solar-shade energy.
	(Dagher *et al.*, 2022)	SI	The study demonstrates that shading effectively minimizes solar transmission and heat gains during extreme weather, offering a viable approach to enhance thermal comfort without reducing daylight availability.
	(Wen, Xie, *et al.*, 2022)	SI	The findings indicate that strategically arranging buildings to maximize solar shading benefits in summer while minimizing negative impacts in winter can significantly improve the energy efficiency of urban buildings across various climatic conditions.
	(Wen, Yang, *et al.*, 2022)	SI	The study reveals that the design of surrounding buildings significantly influences the window-transmitted solar radiation energy (WTSRE) of a target building, and introduces a rapid evaluation method for assessing shading effects during the design phase based on parametric study data.
	(Wang, *et al.*, 2023)	SI	The application of solar shading calculation methods based on existing neighborhood assessment criteria in two case studies proved to be both accurate and effective, with performance further enhanced by the integration of the proposed criterion.

Context	Reference	Method	Conclusions
Global	Hupeng et al., 2019	SI	The results confirm that sound attenuation increases with distance, while reverberation tends to rise with greater façade height and spatial enclosure.
	Leistner et al., 2019	SI	The application of façade absorption materials effectively reduced sound levels, achieving a decrease from 58.6 dB to 52.7 dB.
	Badino et al., 2019	SI	Sound-absorbing façades achieved noise reductions of up to 10 dB, with balcony depth also contributing to the overall attenuation effect.
	Jones & Goehring, 2018	SI	The study concludes that wind-induced noise on perforated facade panels is significantly affected by the panels' geometry and the specific characteristics of the wind.
	Qu & Kang, 2017	SI	The findings show that built form has a substantial impact on wind turbine noise levels, with variations of up to 10 dB observed at distances between 400 and 1000 meters.
	Can et al., 2015	SI	The results indicate that street geometry and surface diffusion can increase sound pressure levels (SPL) by up to 10 dB.
	Hao & Kang, 2014	SI	The study concludes that both urban form and façade absorption play a significant role in shaping the propagation of aircraft noise.
	Van Renterghem et al., 2013	SI	The study finds that fully vegetating source canyon façades offers limited acoustic benefit compared to treating only the upper half when soft bricks are used, while a modest additional reduction of 1 dB(A) is observed with rigid bricks. Vegetation on the lower part of the wall contributes minimally to insertion loss. However, fully vegetating the receiving canyon provides a greater noise reduction effect, achieving an insertion loss of up to 4.4 dB(A) and offering a clear advantage over partial treatments.
	Hornikx and Forssén, 2011	SI	The study demonstrates that open courtyards can experience noise level increases of up to 10 dB(A) compared to closed configurations. Façade openings contribute to higher average noise levels—up to 7.2 dB(A) at façade receiver positions and 10.1 dB(A) within courtyard areas. However, applying sound-absorbing materials to the façade, particularly around the openings, can help mitigate these effects, with absorption achieving reductions of up to 1.5 dB(A). This highlights the importance of façade treatment in managing acoustic exposure in open courtyard designs.
	Oliveira and Silva, 2011	SI	The findings indicate that average Leq values tend to increase with the number of building floors.
	Hornikx and Forssén, 2009	SI	Adjusting the façade absorption coefficient results in approximately a 4 dB(A) reduction in noise levels at most observer positions within urban canyons. Moreover, façade absorption proves most effective when applied to the upper sections of the canyon walls.
	Onaga and Rindel, 2007	SI	The impact of façade scattering on sound pressure levels (SPL) is distance-dependent, with increases observed at short distances that diminish over greater distances. This increase in SPL due to scattering is more pronounced in streets lined with tall façades, whereas in streets with low façades, scattering primarily contributes to a reduction in SPL. Additionally, reverberation time in low-façade streets is influenced by both absorption and scattering coefficients, while in high-façade streets, it is predominantly governed by the absorption coefficient.
	Heimann, 2007	SI	In parallel streets, façades of flat-roof buildings experience lower noise levels compared to those of hip-roof buildings, despite having similar cross-sectional areas. The influence of wind, which causes quieter conditions on upwind façades and louder conditions on downwind façades, is more significant for hip-roof buildings. Interestingly, in parallel street configurations, upwind façades tend to be slightly noisier than downwind façades due to additional exposure to sound propagating downwind from adjacent streets.
	Van Renterghem et al., 2006	SI	Facades with diffuse reflections and balconies significantly enhance noise shielding compared to flat façades, providing approximately 10 dB of additional attenuation near 1000 Hz through architectural features such as window recesses, protruding windowsills, and roughened surfaces. However, shielding effectiveness diminishes notably during downwind sound propagation, especially as wind speed and frequency increase. Conversely, under upwind sound propagation conditions, turbulent scattering limits shielding improvements, resulting in performance comparable to that of a non-moving atmosphere.
	Thorsson and Ogren, 2005	SI	Applying absorptive materials to building façades effectively reduces noise levels at shielded positions, with reductions of at least 5 dB observed when such materials are used within urban canyons.
	Kang, 2005	SI	The study concludes that in the far field, sound pressure levels (SPL) typically decrease by 6–9 dB when the side length of an urban square is doubled. Additionally, reducing building façade height from 50 m to 6 m results in an 8 dB reduction under diffuse boundary conditions. Increasing the length-to-width ratio from 1 to 4 leads to SPL reductions of 5 dB with diffuse boundaries and 2 dB with geometric boundaries. Furthermore, raising the boundary absorption coefficient from 0.1 to 0.9 can lower SPL by 10–12 dB.
	Kang, 2002	SI	The study concludes that sound attenuation along the length of urban canyons is substantial, typically ranging from 20 to 30 dB per 100 meters. It also finds that additional reductions of 2 to 4 dB can be achieved by uniformly increasing boundary absorption or by applying absorbent materials to façades and ground surfaces, with reducing building height producing similar benefits. The study further concludes that introducing gaps between buildings contributes an extra 2 to 3 dB of attenuation, particularly near these openings. Finally, it demonstrates that air absorption enhances sound attenuation at higher frequencies, providing an additional reduction of 3 to 9 dB along the canyon length.

Figure 1. Outline of the methodological approach [4,44,48,52,62,88–112].

The preposed study is grounded in Pedro's theoretical model of urban forms, which is based on configurations commonly found in Portuguese architecture [113]. It builds upon previous research by Oliveira [6], who analyzed noise exposure across different urban morphologies, and Coutinho [87], who examined solar radiation gains using the same foundational urban layouts derived from Pedro's close neighborhood model. All urban forms were applied within a standardized reference area grid of 24,707.52 m^2, with each layout populated through repetition of its base geometry. These forms were assigned numerical identifiers, and their geometric characteristics, along with the parameters used for simulation and analysis, are detailed in Figures 1 and 2.

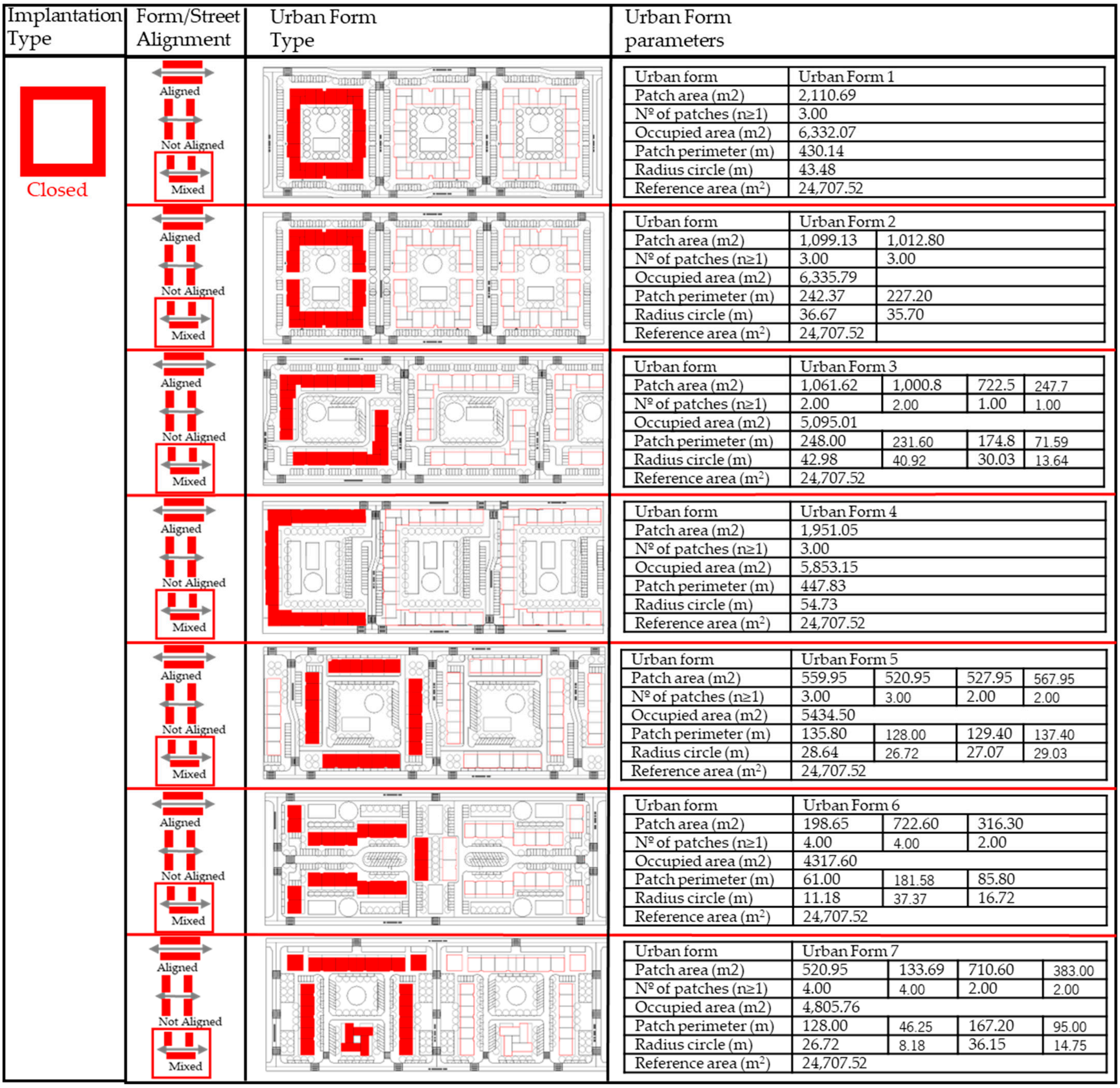


Figure 2. Presentation of the urban forms that have the closed implantation type, identifying the alignment and parameters of each type of urban form.

The purpose of the morphological classification is to define the structural components of urban form more precisely by narrowing their interpretative scope. As outlined by Pedro [113], this classification is based on two key dimensions: the spatial arrangement of building ensembles and their orientation relative to the street layout.

With regard to ensemble placement, three primary configurations are identified: closed, linear, and point-based (or punctual). In a closed arrangement, buildings collectively enclose exterior space, with gaps between structures not exceeding one-quarter of the total perimeter. A linear arrangement maintains partial enclosure, with gaps between buildings ranging from one-quarter to half the perimeter length. By contrast, point-based arrangements feature wide separations—greater than half the total perimeter—resulting in a loosely defined or undefined exterior space.

In terms of street alignment, buildings may be placed using aligned, non-aligned, or mixed strategies. Aligned placement refers to buildings arranged consistently along the street frontage, while non-aligned placement allows for greater spatial freedom, independent of street orientation. Mixed placement combines elements of both. For the purposes of this study, only the aligned placement strategy is applied, as illustrated in Figures 2 and 3.

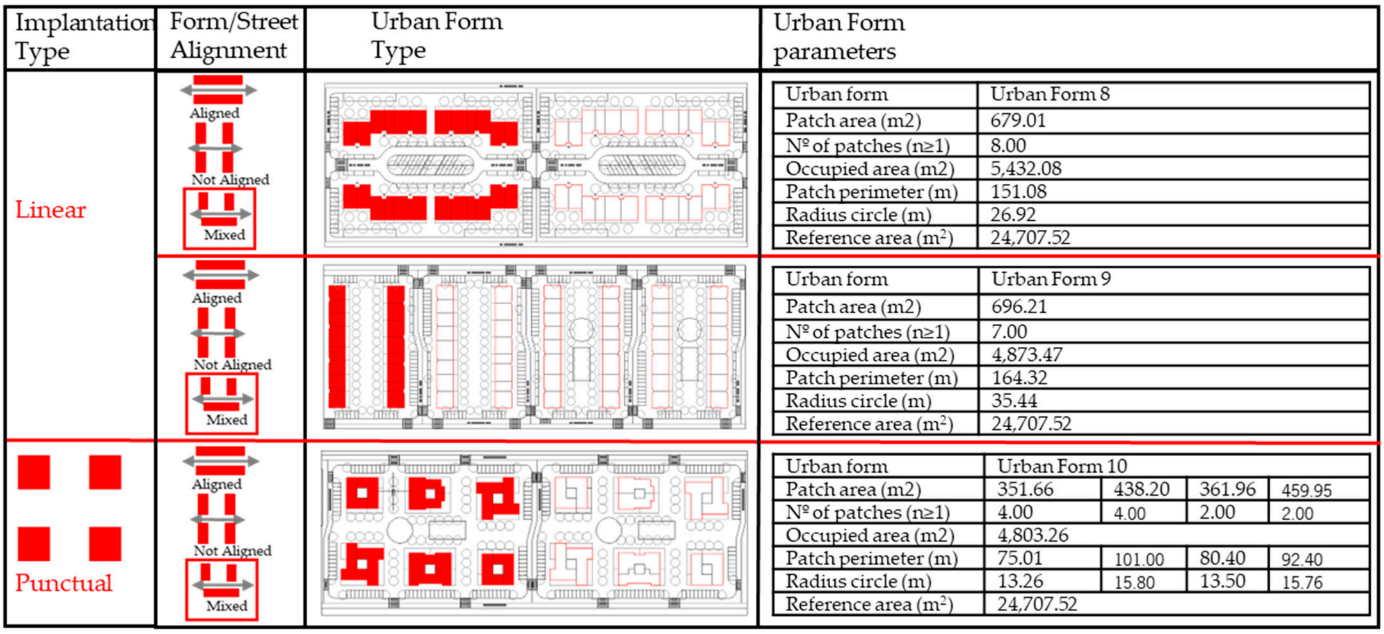


Figure 3. Presentation of the urban forms that have the linear or punctual implantation type, identifying the alignment and parameters of each type of urban form.

In order to systematize the analysis of the urban forms selected from Pedro's model [113], Oliveira [6] and Coutinho [87] adopted a constant height of 4 floors, with a ceiling height of 3 m, including the ground floor, giving a total height of 12 m. These assumptions were adopted in both studies, enabling the former to establish relationships between noise exposure levels and the urban form indicators tested and the latter to establish relationships between the solar energy incident on the façades and the same form indicators.

Coutinho [87] excluded four forms from the study, not considering the irregularities and asymmetries observable in the total universe of forms studied, thus guaranteeing some uniformity of solar exposure (namely by orientation), perfect patterns of symmetry or repetition and a perceptible homogeneity of patterns (so urban forms 3, 4, 7 and 9 were excluded).

The methodology developed by Coutinho [87] aimed to demonstrate how urban form influences a building's energy needs. How solar gains in its vertical envelope, depending on the type of urban form used, can reduce its energy consumption. Or how the layout of the urban form in the face of noise exposure can, even at the design stage, avoid potential problems caused by the form of the buildings, minimizing exposure discomfort.

In the first study, Oliveira [6] used the CadnaA—Computer Aided Noise Abatement—software to calculate the noise levels on the façades, which uses the NMPB 96 noise prediction method, recommended by establishing common methods for the assessment of noise in accordance with Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 [114]. Using this software, the calculation was carried out using a quadrangular grid along all the façades with a dimension of 1.5 m × 1.5 m and a distance from the façade of 0.5 m. These scenarios were designed using a grid measuring

210 m by 140 m, resulting in a total gross floor area of 29,400 m^2 and a perimeter of 700 m. Each scenario includes access via two local roads characterized by the following features:

- Asphalt surface with no slope.
- Traffic volume of 300 vehicles per hour, including 5% heavy vehicles.
- A speed limit of 50 km/h.
- Reflection order: 2.
- Output: Leq (A).
- Favorable meteorological conditions to sound propagation.
- Temperature: 15 °C.
- Humidity: 70%.

In the second study, Coutinho [87] used Revit Solar Analysis modeling software to calculate the amount of solar radiation (direct radiation (Ib), diffuse radiation (Id), radiation reflected from the ground (Ir)) that reaches a given surface (façade and roof) during a given period of time. This study concluded that it was not possible to establish an acceptable correlation for the summer season, unlike the heating season. The analysis was therefore restricted to the winter season (time period is provided for in the Regulations for Residential Buildings (REH)) [115] and does not take reflected radiation into account, as there is no spectral information on the simulation of the exterior surfaces.

The CLIMAS-SCE v1.0 software, provided by the LNEG (National Energy and Geology Laboratory) [116] and developed specifically for the National Building Certification System, is used to obtain the climatological statistics and the Reference Meteorological Year of the desired location in order to carry out dynamic simulations of systems and buildings. The data exported by the software are corrected for the altitude of the location (city of Braga, north of Portugal) and with the following calculation parameters:

- No specific materials were assigned to the building shapes or exterior parts, so conceptual masses are used.
- The simulation was based on weather data from the city center of Braga.
- The study uses cumulative solar radiation values to better understand the total amount of sunlight hitting the buildings.
- The heating period starts in the second third of October, when average temperatures drop below 15 °C.

Following on from the calculation and presentation of the models for forecasting and simulating urban forms that have been presented, Figure 4 presents simulation maps of urban noise and solar radiation for the selected urban forms, illustrating the conflicting nature of optimal performance in relation to noise exposure and solar capture.

As shown, noise levels generally decrease when physical features, such as recesses or inner courtyards, are present, as these elements create zones of acoustic shadow. Conversely, solar radiation is more effectively captured in urban forms that are compact and linear, where fewer obstructions allow for greater solar exposure. In contrast, forms with elements like patios tend to experience reduced solar gains due to shading and interruptions in the building layout.

Ultimately, this approach assessed the correlation between urban form and the levels of solar exposure of the façades and the levels of noise reaching the façade by calculating urban form indicators, represented in Table 1 (Calculation forms and calculation parameters).

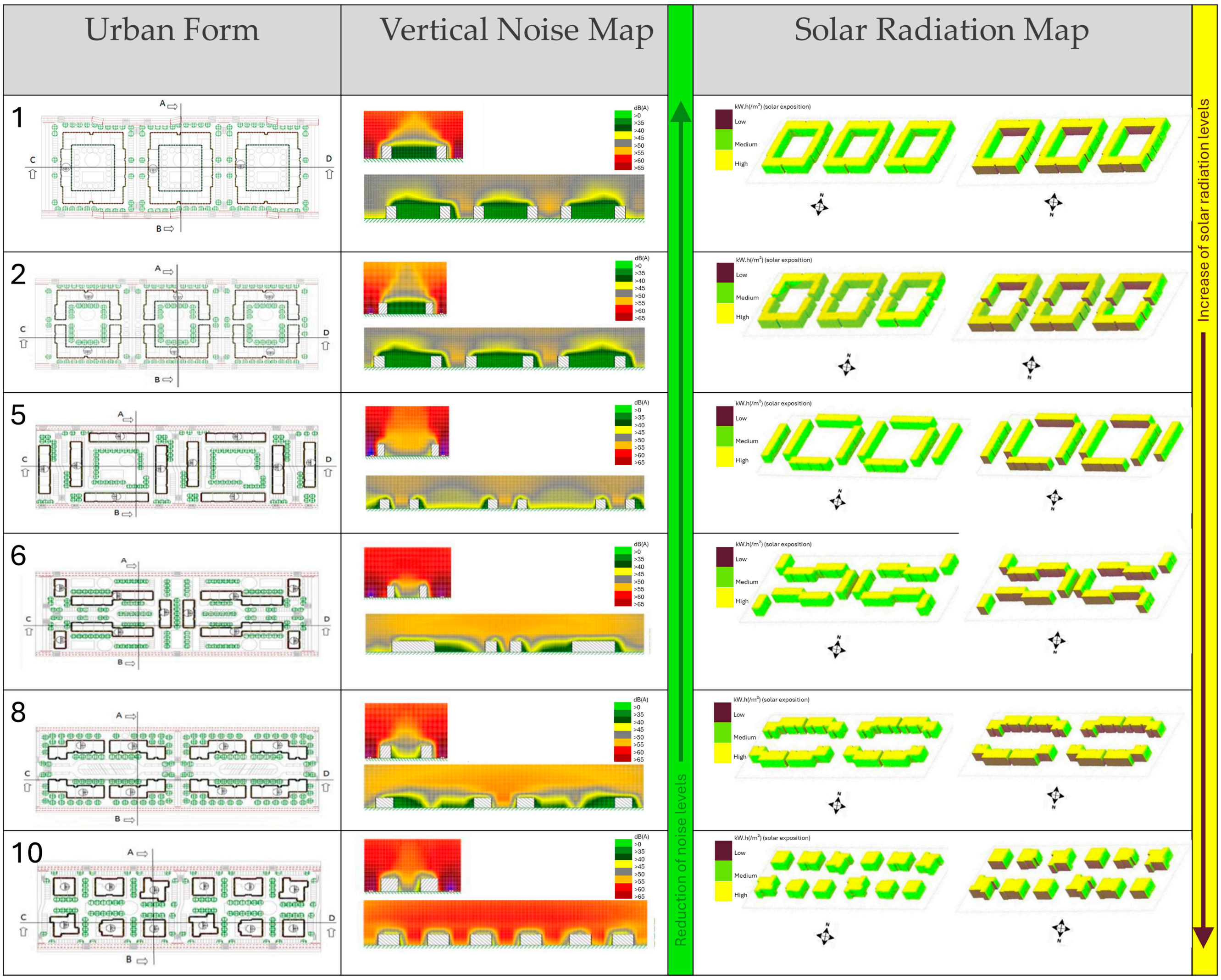


Figure 4. Urban Form Simulation (Noise and Solar Radiation Maps).

Table 1. Urban Form Indicators.

Urban Form Indicators	Compactness Index (CI)	Porosity Index (ROS)	Perimeter Complexity Index (Fractal)
Calculation formulas	$CI = \frac{\sum \frac{P_i}{p_i}}{n} = \frac{\sum \frac{2\pi\sqrt{\frac{s_i}{\pi}}}{P_i}}{n}$	$ROS = \frac{s'}{s} \times 100\%$	$fractal = \sum_{i=1}^{n} \left(\left(\frac{2\ln\left(\frac{p_i}{2\sqrt{\pi}}\right)}{\ln s_i} \right) \left(\frac{s_i}{\sum_{i=1}^{n} s_i} \right) \right)$
Calculation parameters	si: patch area, [m^2] pi: perimeter of the urban area, [m] Pi: perimeter of the circle with area si, [m] N: total number of urban patches	s′: sum of the area of all the "voids" within the extracted urban area, [m^2]; s: sum of the area of all patches and all voids (total urban area), [m^2].	pi = perimeter of the patch i, [m] ai = patch area of i, [m^2]; n = number of urbanized areas that make up the urban zone, [-].

In the proposed study, each built-up block depicted in Tables 2 and 3 was treated as an individual patch, with its corresponding area and perimeter measured accordingly with each urban indicator. The total area (s) was defined as the reference area, representing the combined footprint of all the built-up blocks within the study set.

4. Case Study

In this Section, we detail how the three urban form indices—Compactness Index (CI), Porosity Index (ROS), and Perimeter Complexity Index (Fractal)—were quantitatively related to noise levels and solar radiation exposure. The urban forms previously modeled by Oliveira [6] (for noise) and Coutinho [87] (for solar radiation) were analyzed using identical base geometries and configurations derived from Pedro's urban layout model. For each form, the three morphological indices were calculated based on geometric parameters of the built volumes and their spatial distribution. The resulting index values were then cross-referenced with the following simulated outputs: façade noise levels obtained through CadnaA and solar radiation data from Revit's Solar Analysis tool (focusing on winter season gains). Tables 2–4 and Figures 5–7 present the comparative trends observed between each index and the respective environmental performance metrics, enabling the interpretation of how specific urban morphologies influence noise propagation and solar capture. This method allows for the identification of morphological patterns that either enhance or mitigate environmental exposure.

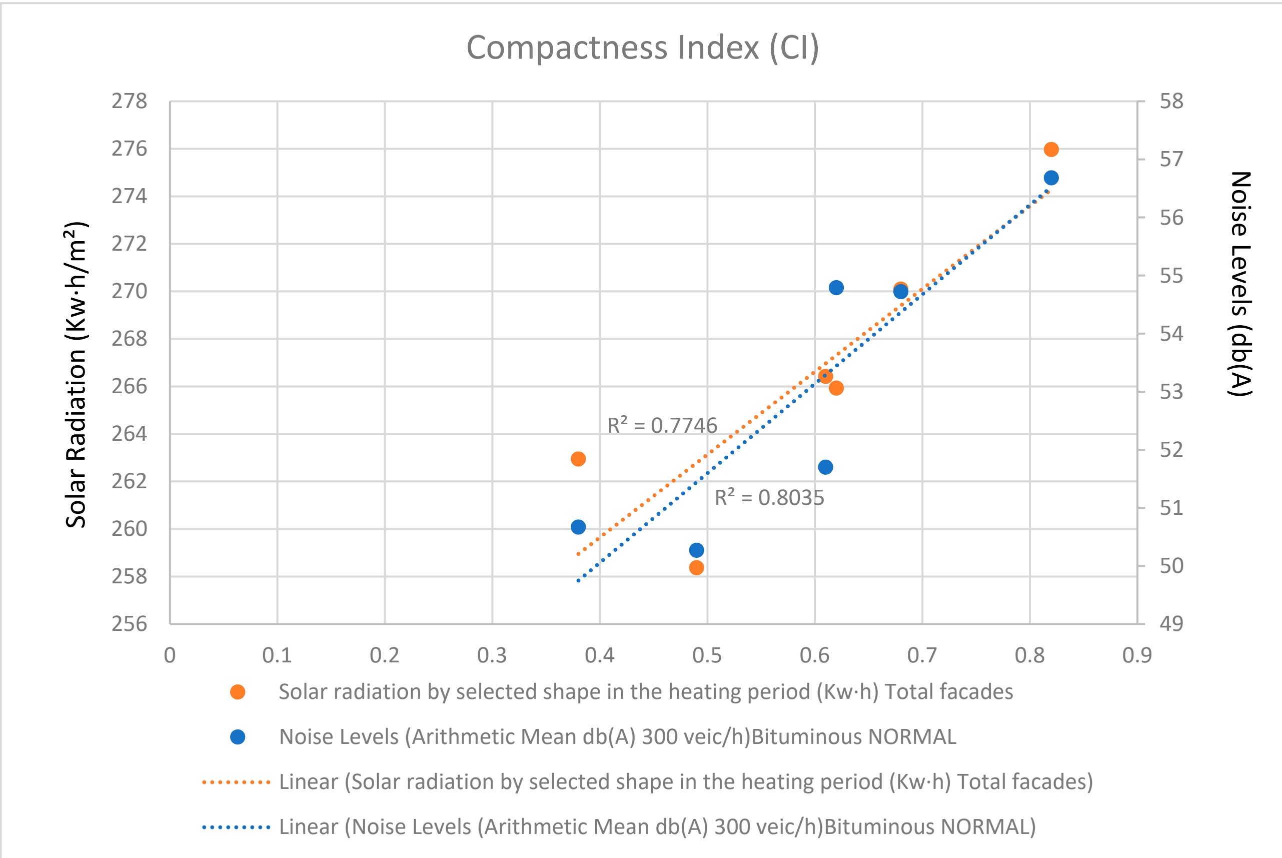


Figure 5. Compactness Index (CI) graph that identifies the relationship between the three variables and exemplifies the tendency line.

The case study highlights the opposing behavior of these variables when influenced by the same urban forms. Calculating three form indicators (Table 1), namely the Compactness Index (CI), the Porosity Index (ROS) and the Perimeter Complexity Index (Fractal), allows us to compare and relate the six urban forms and draw some conclusions.

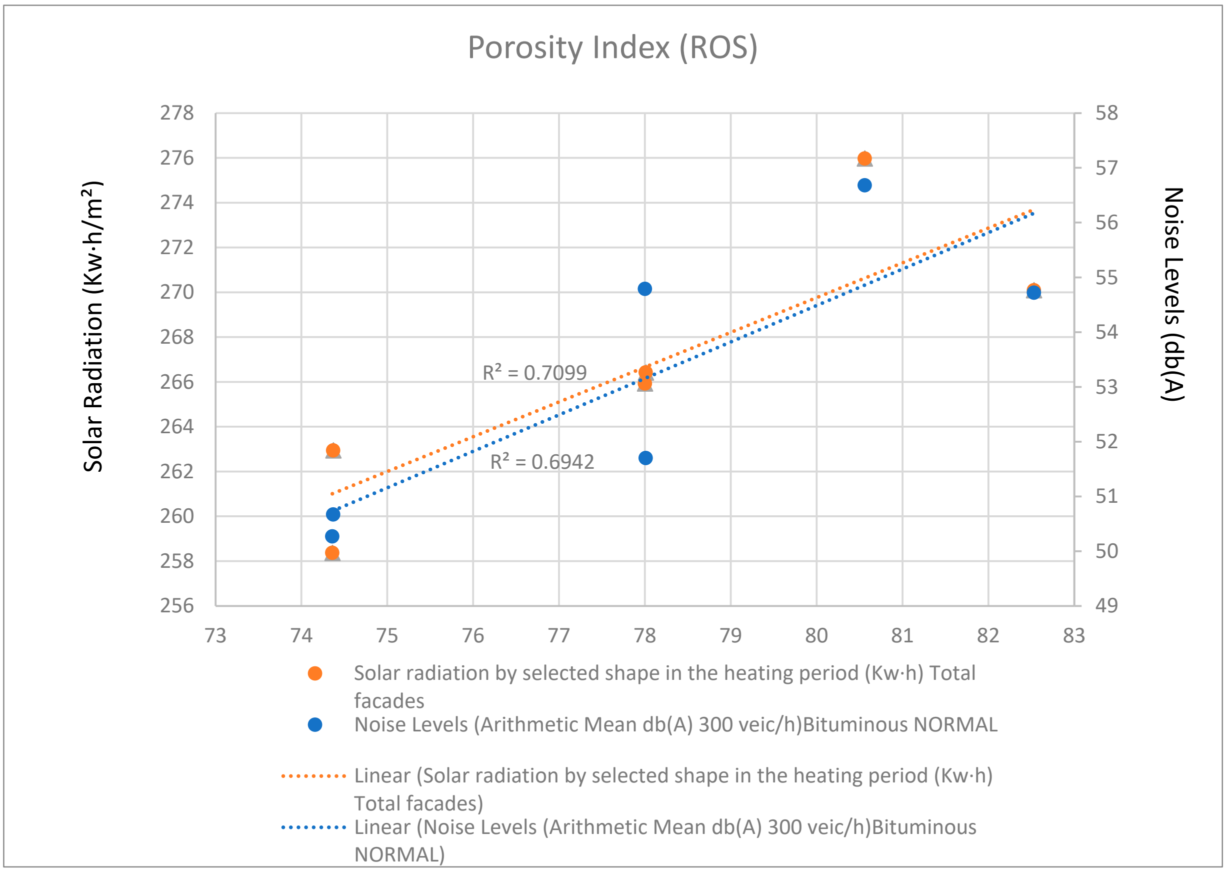


Figure 6. Porosity Index (ROS) graph that identifies the relationship between the three variables and exemplify the tendency line.

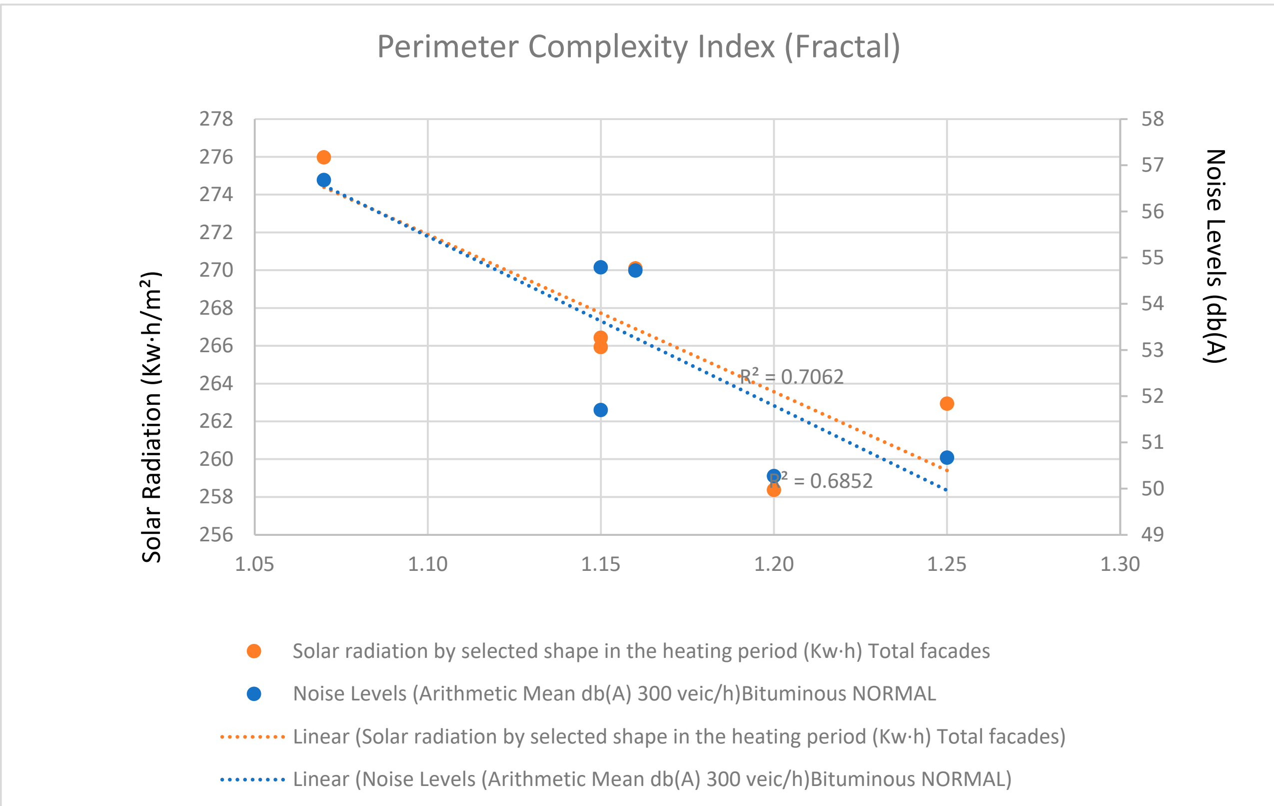


Figure 7. Perimeter Complexity Index (Fractal) graph that identifies the relationship between the three variables and exemplify the tendency line.

Table 2. Compactness Index (CI).

Urban Form	Compactness Index (CI)	Noise Levels (Arithmetic Mean dB (A) 300 Vehicles/h) Normal Bitumen	Solar Radiation (by Selected Form in the Heating Period (kW·h)/Total Façades (m^2))
1	0.38	50.67	262.94
2	0.49	50.27	258.37
8	0.61	51.70	266.42
5	0.62	54.79	265.93
6	0.68	54.72	270.09
10	0.82	56.68	275.97

Table 3. Porosity Index (ROS).

Urban Form	Porosity Index (ROS)	Noise Levels (Arithmetic Mean dB (A) 300 Vehicles/h) Normal Bitumen	Solar Radiation (By Selected Form in the Heating Period (kW·h)/Total Façades (m^2))
2	74.36	50.27	258.37
1	74.37	50.67	262.94
5	78	54.79	265.93
8	78.01	51.70	266.42
10	80.56	56.68	275.97
6	82.53	54.72	270.09

Table 4. Perimeter Complexity Index (Fractal).

Urban Form	Perimeter Complexity Index (Fractal)	Noise Levels (Arithmetic Mean dB (A) 300 Vehicles/h) Normal Bitumen	Solar Radiation (By Selected Form in the Heating Period (kW·h)/Total Façades (m^2))
10	1.07	56.68	275.97
5	1.15	54.79	265.93
8	1.15	51.7	266.42
6	1.16	54.72	270.09
2	1.2	50.27	258.37
1	1.25	50.67	262.94

4.1. Compactness Index (CI)

The Compactness Index is a reflection of urban density patterns. Denser areas with uniform shapes tend to exhibit higher CI values (Table 2), as they minimize unused spaces between buildings and infrastructure. However, this density may exacerbate issues like heat retention and sound amplification.

Regular urban forms with higher CIs can increase exposure to environmental challenges, such as urban noise. This relationship arises from the tendency of sound to propagate more uniformly across regular, contiguous urban forms, as indicated by the Noise levels in Table 2, showing higher noise levels with increasing regularity.

What influences the CI is the regularity of the form and although the regularity of the six Urban forms is different, the trend line shows a tendency for noise to increase as regularity increases. The Compactness Index (CI) shows the minimum value for Form 1, but the maximum value is attributed to Form 10, which is the most regular as it is possible to verify in Table 2. The Compactness Index increased from 0.38 to 0.82, and the noise level increased from 50.67 dB(A) to 56.68 dB(A) and solar radiation levels increased from 262.94 kW·h/m^2 to 275.97 kW·h/m^2.

The more regular the urban forms, the less likely it is that shadow zones will form, i.e., zones protected from noise exposure. As you might expect, noise increases as the regularity of the forms increases, as it is possible to verify in Figure 5.

As can be seen in the graph, there is a tendency for solar radiation to increase as the Compactness Index rises. Knowing that the higher the value of this index, the more regular and compact the form, it is also to be expected that under these circumstances, there will be less shading on the façades and consequently greater solar radiation gains, which is in line with the observed trend.

4.2. Porosity Index (ROS)

The value of this form indicator increases according to the number of open spaces, i.e., the more open spaces, the lower the number of obstacles, and consequently the lower the shading areas, which influence the increase in exposure to solar radiation (Table 3).

As can be seen in Table 3, and in Figure 6, it was expected that the higher indices would correspond to urban forms with greater solar radiation gains. The Porosity Index (ROS) measures the relationship between the unbuilt space and the Reference Area, where Form 6 has the most empty spaces, and the relationship with noise is directly proportional, i.e., as the ROS increases, so do the noise levels. This can be explained by the fact that the greater the permeability of the urban form, the easier it is for sound waves to reach all building facades. In relation to the other forms, Form 1 and Form 2 have the highest utilization of the Reference Area and therefore the lowest ROS. The Porosity Index (ROS) shows the minimum value for Form 2, but the maximum value is attributed to Form 6, and the index increased from 74.36 to 82.53.

The Porosity Index increases with the number of open spaces, resulting in fewer obstacles and smaller areas of shade, increasing exposure to solar radiation. Urban forms with higher indices tend to have higher solar radiation gains. The Porosity Index (ROS) measures the relationship between the unbuilt space and the reference area and is directly proportional to noise levels: the higher the ROS, the greater the propagation of sound waves.

4.3. Perimeter Complexity Index (Fractal)

Contrary to the correlations established for the previous form indices, it is possible to observe a tendency for solar radiation to decrease with increasing Perimeter Complexity (Fractal) as can be seen in Table 4.

This result was to be expected considering that the Fractal index increases with the complexity of the form (protrusions, concavities, convexities, irregularities) producing areas of shading on the façades, and consequently lower solar radiation gains, which is in line with the observed trend visible in the graph of Figure 7.

The Perimeter Complexity Index or Fractal, as mentioned, measures the regularity and complexity of the forms, where Form 1 (1.25) has the highest value and Form 10 (1.07) the lowest. The Perimeter Complexity Index decreased from 1.25 to 1.07, and the noise level increased from 50.67 dB(A) to 56.68 dB(A). As presented, the noise level increases, as the Fractal value decreases; namely, the more complex the forms, the more shadow spaces are created, thus the lower the permeability and exposure to noise.

5. Discussion

The observed results are in line with expectations and the three correlation analyses lead to the conclusion that solar radiation and noise exposure are influenced by the form and volume of the building and its surroundings, in particular, their compactness, the area of open spaces or the simplicity of the shape of the urban area.

In addition to the factors already mentioned, solar radiation is influenced by shading and the form indicators portray the impact of this variability, i.e., an increase or reduction in shading areas alters the solar gains that reach the façade and the urban forms analyzed in the study portray this variability.

In particular, in the heating season (winter), the effect of shading is very significant in a given scenario due to the low height of the sun during the season.

In this sense, it was expected that urban forms with a more linear form and volume would be more conducive to unobstructed transmission/capture of solar radiation (low shading on the building envelope, particularly the vertical one), allowing for a range of façade exposure favorable to increased exposure to solar radiation.

Urban forms with more complex forms and volumes, with concavities and recesses or interior courtyards, generate shading effects on the neighboring façades, normally reducing exposure to solar radiation, as already mentioned.

In this assessment, Form 10 has the highest incident radiation values, because it is a simple urban form and consequently has equally high Compactness and Porosity values and a low Fractal value. Forms 1 and 2, being less compact and porous, have low incident radiation values and high Fractal values, as they are complex forms with an inverse trend to Form 10.

However, in terms of noise exposure, it is beneficial for urban forms to have complex forms and volumes, and preferably with interior courtyards, like Form 1, in order to create acoustic shading zones, i.e., noise exposure reduction zones.

In the same vein, the acoustic shading that urban forms promote influences the noise exposure levels that reach the façades. Therefore, Form 1 has the lowest noise exposure and Form 10 is the most exposed to noise. Form 10 has 56.68 dB(A), which is 6.01 dB(A) higher than Form 1, as it has no acoustic shading areas.

6. Limitations

This study presents some noteworthy limitations. One of the main constraints is its scope—while it does not intend to serve as a comprehensive manual of standard solutions, it is also not feasible to address all urban typologies, their variations, and potential conflicts.

Given the understanding that no universal, transferable typologies exist, there are likewise no ideal solutions applicable to every specific case. However, this work aims to encourage the integration of these correlations, particularly during the early design phase.

Throughout this preliminary approach, and in reviewing the studies by Oliveira (2011) [6] and Coutinho (2018) [87], certain limitations emerged—specifically those directly related to the urban form indicators used, as well as the scope of the selected form models.

The indicators (CI, ROS, and Fractal) employed in both studies are typically applied to large urban areas rather than individual blocks or the neighborhood-scale forms adopted in this research. To address this, the same building height was used across all urban forms to maintain consistency.

The next phase of the research will aim to address some of these limitations by refining the study and focusing on a more detailed analysis of one to three selected urban forms.

Form 10 and Form 1 have been identified as candidates for further exploration, as they represent ideal and non-ideal conditions in the respective studies. These forms are inversely related: Form 10 represents the optimal urban layout for maximizing solar radiation on façades due to its simple, linear, and compact volume.

However, the same characteristics that enhance solar exposure in Form 10 also make it the least favorable in terms of noise exposure. Its lack of recesses or volumetric complexity means it does not generate acoustic protection zones (acoustic shadow areas), which could otherwise reduce noise levels.

To address these "incompatibilities", it is essential to further investigate these areas of conflict, taking into account the parameters and requirements involved in calculating both solar and noise exposure levels.

7. Conclusions

In this approach, the combination of the two studies, using the same urban form model, made it possible to establish some conclusions based on the correlation of the results obtained in each of the studies with the urban form indicators.

Namely, urban Form 10 provides the greatest energy gain in the winter period and Forms 1 and 2 provide the least energy gain in the same period. It can be seen that Form 1 has low values for the Compactness Index and the Porosity Index, while achieving one of the highest values for the Perimeter Complexity Index. On the opposite side is Form 10, which has high values for the Compactness Index and the Porosity Index, obtaining the lowest value for the Perimeter Complexity indicator.

As already mentioned, this can be explained by the direct relationship between the compactness and the amount of open space of the urban form. The greater the compactness, the more solar radiation enters. In turn, less complex forms lead to less solar shading, leading to greater energy gain. Form 10, with the lowest Fractal Index value, corroborates this deduction.

On the other hand, Forms 1 and 2, with the lowest Compactness and Porosity Indices and the highest Perimeter Complexity, have the lowest solar gains. It can be concluded that there is an increase in energy gains from solar radiation as the Porosity and Compactness Indices increase. Conversely, as the Fractal Index increases, there is a reduction in energy gains from solar radiation.

On the other hand, in terms of reducing noise exposure, the process is reversed in terms of solar radiation incidence. In other words, as the Compactness and Porosity Indices increase, there is also an increase in noise exposure, which in this case is not beneficial. In this sense, the aim is for noise exposure levels to be reduced rather than increased. In turn, the Fractal Index represents the desired trend, i.e., as the complexity of urban form increases, noise exposure levels decrease.

The study developed proved to be useful and appropriate, allowing us to demonstrate the combined influence of urban form on solar gains in the vertical envelope of buildings, or how it behaves in relation to noise exposure.

The aim of this approach was to find out which urban forms behave best and worst in relation to noise exposure and the incidence of solar radiation, making it possible to compare and relate urban forms to solar radiation and urban noise.

Given these findings, urban planners and architects can leverage this methodology to create balanced urban environments that promote energy efficiency and acoustic comfort. The results underscore the necessity of considering urban form indicators in early-stage design decisions, particularly in regions with strict regulations on thermal and acoustic performance. The identification of Form 10 as optimal for solar exposure and Form 1 as the most effective for noise reduction suggests that mixed-form solutions or hybrid urban layouts may be necessary to achieve a balance between these competing demands.

The considerations presented highlight the potential of these indices as tools to support planning in the field of solar exposure and noise exposure in the study and regulation of new constructions.

Future research could explore the application of these indicators in different climatic contexts, urban densities, and architectural typologies to refine predictive models further.

Additionally, integrating other environmental factors, such as wind flow and air quality, could provide a more comprehensive approach to sustainable urban design. The potential for these indices to serve as regulatory benchmarks highlights their usefulness in shaping future policies for energy-efficient and acoustically comfortable urban developments.

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