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# Seismic and solar performance of historical city Urban form-based multicriteria analysis

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**Abstract**. The understanding of the global performance of a historical city is a complex balance of several specific issues and requires a multi-disciplinary approach to face with actual urban phenomena and challenges, such as the seismic risk and energy efficiency, that are strongly influenced by urban form. This paper focuses on the potential of urban metrics and typological indicators for describing the seismic vulnerability and the solar radiation availability of distinct urban textures, and the correlation between the two aspects. Comparative analysis at fabric scale was conducted on the historical centre of Rieti (Latium, Italy), to underline the main seismic and solar indicators. In the last decade, we witnessed the spreading of urban scale assessment and analysis tools, but seldom using an integrated approach to face the complexity of the historical city. Relying on morpho-typological indicators, the proposed method characterizes the fabrics in terms of seismic vulnerability and solar availability through a multicriteria analysis. The analysis reveals substantial differences between fabrics using three groups of indicators: *Plan*, *Space* and *Analysis-oriented*. Each group describes different features of the urban fabrics that affect seismic and solar performance and suggests improvement strategies. The purpose is to support policymaker and designer in the urban renovation process.

## 1. Introduction

The historical city is a complex system, and the understanding of its evolution requires specific attention to face urban actual phenomena and challenges, as natural disasters and climate changes. Nowadays, several studies in the field make use of approaches at the urban scale, rather than the building scale, in order to consider and explore all the elements that affect the functioning of a city [1–4]. Moreover, different urban forms correspond to different performances among which the seismic and the solar performances must resort to the analysis of the physical features of basic components of the built environment. In this framework, our study explores the causal relation urban form/seismic vulnerability/solar energy in the historical city through a multicriteria analysis, based on physical indicators - Urban Metrics (UM) and Morpho-Typological Indicators (MTI). The aim is to ease planning decisions for sustainable renovation processes.

The Mediterranean city represents a significant example of urban system, based on masonry construction and characterized by typological processes of growth, closely related to climate conditions and seismic events that defined its history. In terms of seismic risk, the analysis of the urban fabric focuses on the mechanical behaviour at the scale of the building aggregate [5], defined as a complex system of interrelated parts, structural units that are interconnected or in contact, which may interact under a seismic or dynamic action in general. Building aggregates generally have non-homogeneous and stratified constructive features, with different level of effectiveness of structural links between different parts. The research aimed at understanding the seismic performance of the city has developed the following approaches: on the one hand the structural-constructive approach focused on the analytical-mechanical understanding of masonry construction [6,7] and the identification of constructive characteristics linked to the reduction of vulnerability on an urban scale [1,2]; on the other hand the urban-systemic one [8,9] focused on risk assessment for the functional systems in which the city is organized. The shift of attention from the scale of the building to the aggregate and urban fabric one revolves around the morpho-typological parameters, which together with the constructive ones, are the basis for expeditious assessments of vulnerability on the urban [2,10] and territorial scale [11].

Solar energy availability is a key variable to assess buildings energy performance in the urban environment. On one hand, building's solar gains account for a significant part of the energy balance during both winter and summer; on the other hand, the potential for harvest solar energy in the urban context is directly connected to the potential for renewable energy systems to enhance energy efficiency at urban scale. Several studies reported the effect of urban metrics on solar performance [12,13]. Some of them consider real urban areas and related data in order to predict their solar potential using UM to better characterize the layout of the case studies [14,15]. Other studies focused on understanding the influence of urban morphology, described and controlled through UM, to optimize the solar potential of urban areas. The latter use normalised models derived from representative urban textures [16,17]. To perform solar energy analysis at urban scale, experts use specialised tools recently developed for the purpose, i.e. *Radiance*, *DIVA*, *CitySim* and *SUNtool*. These tools fostered the implementation of solar analysis in design practice. However, two factors still limit their widespread to urban planning and design: the specialist knowledge required to set up the simulation and the amount of time needed to realize the model at urban scale. For these reasons, this study uses the capability of UM to predict solar energy availability at urban scale. The method, based on a previous study reduces time and data necessary to carry out solar analyses, useful in the early stage of the design process [18]; this method is intended for architects and decision makers since do not require specialist knowledge and data required for the calculation are generally used in urban planning practice and are easily accessible for many cities.

In the last years, the importance of integrated approaches between energy and seismic analysis is testified by a growing number of studies. The relevance is particularly highlighted regarding the retrofit of the built heritage, implementing building envelope systems for energy, structural, and user-oriented retrofit that would significantly increase the commercial value and the life cycle of buildings, involve the users in attractive and visible solutions and, reduce the costs of energy [19]. Other studies regard the renovation of a high-rise building, focusing on the architectural quality to demonstrate the cost-effective evaluation of the convenience of the integrated approach in supporting public administration in social housing renovation [20]. On the one hand, the importance of the urban scale is nowadays recognized and investigated in several types of research for both the energy and the seismic performance, focusing the influence of urban morphology on these features [21]. On the other hand, the integration of the approaches is still focused on the building scale. The aim of this research paper is to overcome this compartmentation of knowledge, proposing a preliminary approach on integrated multicriteria analysis for the historical city, based on morpho-typological indicators in order to describe the seismic vulnerability and the solar radiation availability.

## 2. Methodology

### *2.1. The city of Rieti*

The city of Rieti, located in Central Italy, is the ideal urban environment to test seismic and solar performance of historical urban form. Rieti concerned with the category of medium sized (between 5,000 and 60,000 inhabitants) local council areas, which make up about 30% of the total of Italian local government bodies and concern over 50% of the population - Ancitel on Istat database (01/01/2018).

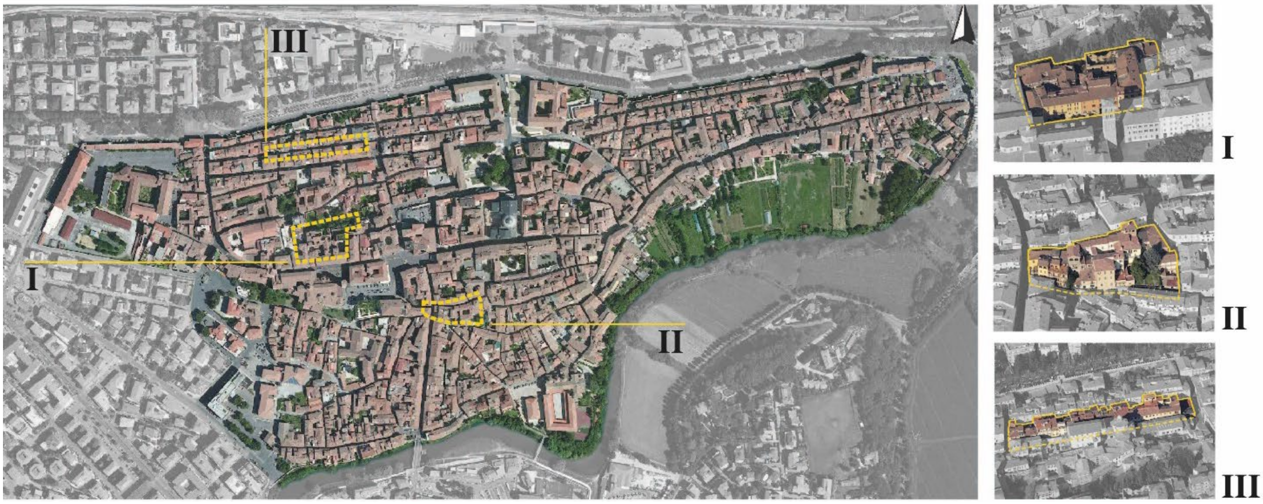


**Figure 1** Aerial view of the city of Rieti and case studies identification.

The municipality of Rieti is characterized by well-conserved historic centre covering an area in proportion to its population and which falls in an area of medium-high seismic risk (zone 2), the area recently stroke by the 2016 Central Italy Earthquake. Case studies are three representative aggregates of typical urban texture of Rieti: case **I** is located in the core of the roman town, following the ancient settlement, along the *decumanus*; the aggregate, as a portion of an urban texture characterized by a clear hierarchy of streets and public space, is the result of stratification and alteration of the original seventieth century buildings; case **II**, close to the medieval walls, is part of a more articulated urban fabric with narrow streets; case **III** is located in the first medieval expansion, with a regular street pattern and mainly based on row houses, partially modified or replaced in recent times.

*2.2. Metrics for urban form analysis*

The range of variation of several Urban Metrics (UM) and Morpho-Typological Indicators (MTI) have been calculated. The formers have been derived from three-dimensional models of the urban textures with a level of detail LoD1 [22]. The latter have been derived from typological-observational methods, based on data of damage and vulnerability observed on previous earthquakes and normally calibrated on the use of existing databases with a level of accuracy 1 [7]. The UM taken into account have been derived from eight basic variables, widely common in urban and building studies and easily accessible (Table 1). Each metric gives information on some qualitative aspects of the urban form, such as the shape of the buildings, the plot patterns or the street network. It has been already proven that UM have a causal relation with energy performance at the urban scale [3,23]. Morpho-typological indicators are derived from the observational approach on the damage of similar structures, common in vulnerability studies for expeditious assessment at urban and territorial scale. Each indicator gives information on some qualitative aspects of the urban form and structural behaviour of the aggregate, such regularity of shape, interactions with existing buildings, transformations and interventions (Fig. 2 Table 2). The MTI analyzed are derived from the studies conducted on the case study of Nocera Umbra [24] and from the studies of Borri and Avorio, carried out on the masonry construction. In analogy with Fazzio's studies [24], qualitative indicators have a variable weight ranging from 3 to 10.

Both UM and MTI have been divided into three groups, considering their peculiarities in describing urban form: *Plan, Space* and *Analysis-oriented*. Besides, in order to facilitate the understanding and of the results, a comparison between cases has been conducted by means of normalization (Table 2). The groups collect UM and MTI with similar properties in terms of description of different features of the aggregates: *Plan* indicators are able to represent the main features on the horizontal plan; *Space*

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indicators describe the three-dimensional complexity; *Analysis-oriented* indicators are useful to predict solar and seismic performance at early stage of analysis.

### *2.3. Aggregate seismic and solar performance*

The "vulnerability of the aggregates" is defined as the susceptibility to damage and loss of organization due to the complex of risk factors to which individual blocks are subjected, deriving from typo-morphological, structural and functional aspects [24]. In this study, we refer to "relative vulnerability" of the aggregates, because the normalization is carried out on the dataset of each city. Given the typological-observational nature of the vulnerability assessment methodology, the results have a greater relevance for the urban management in order to understand the vulnerability level of different portion of the urban texture.
Analogous to the cited studies, the seismic performance has been analysed thought two group of indicators, as part of a wider research [10]: descriptor parameters of the morphological and typological characteristics of the aggregate, related to the overall configuration; descriptor parameters of the general structural characteristics, related to the average characteristics of building components and aggregation methods. In this paper the first group of indicators have been considered (Figure 2).

The solar irradiation on building façades has been assessed for the selected urban aggregates of each digital model, considering urban obstructions during the whole year. We focus on the solar performance of the vertical surfaces since they are directly related to the building's solar gains which account for the most part of the energy demand in the Mediterranean latitudes. *Heliodon2* software and *Heliodon2plus* data post-processor have been used for simulations. *Heliodon2* calculates the spatial and temporal distribution of solar energy on building façades, considering a cloudless sky condition during a given period; the associated post-processor use climate data to obtain direct and diffuse solar radiation. Calculations have been carried out on the base of the latitude of the city of Rieti (42°24' N 12°51' E).

## 3. Results and discussion

The main results, with regards to solar irradiation on building façades and seismic performance, UM and TI evaluation are here presented and discussed in two separate subsections. The results have general implications to seismic and solar performance at urban scale in the historical city of Mediterranean climate.

### *3.1. Seismic and solar performance*

The assessment of seismic vulnerability for the aggregates shows the most critical situations for the cases with higher Sd or TAd, which is usually reflected also on articulated geometric configurations (**I**), and for irregular aggregates with high values of PT, PTis and AT, located in complex urban fabric. The latter due to the relation with the surrounding aggregates (rSA) increasing the induced vulnerability (**II**). On the contrary, case **III** emerges as relatively less vulnerable as described by lower PT (regular linear trend) and lower TAd (mainly composed of building with a high degree of typological homogeneity). In order to complete the seismic analysis and to evaluate the relative vulnerability index, indicators based on structural characteristics are reported in Table 3.

**Table 1** Urban metrics basic variables.

| Symb. | Unit | | I | II | III |
|---|---|---|---|---|---|
| **P** | [inhab.] | Population | 646 | 382 | 374 |
| **A** | [m$^2$] | Base land area | 5362 | 3482 | 4396 |
| **C** | [m$^2$] | Footprint | 3693 | 2288 | 3117 |
| **F** | [m$^2$] | Gross floor area | 15095,4 | 9222,64 | 9817,41 |
| **S** | [m$^2$] | Façade surface | 10216,5 | 7131,4 | 5711,2 |
| **V** | [m$^3$] | Built-up volume | 64571 | 38236 | 37403 |
| **$L_i$** | [m] | Interior network | 0 | 0 | 0 |
| **$L_e$** | [m] | Edge network | 325 | 266 | 377 |

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**Table 2** Values of morpho-typological indicators and urban metrics regarded to case studies.

| | | **Plan** | **I** | **II** | **III** |
|---|---|---|---|---|---|
| **FSI** | [$m^2/m^2$] | Building intensity | 2,82 | 2,65 | 2,23 |
| **FSd** | [inhab./$m^2$] | Floor space density | 0,04 | 0,04 | 0,04 |
| **GSI** | [$m^2/m^2$] | Coverage | 0,69 | 0,66 | 0,71 |
| **N** | [m/m] | Network density | 0,030 | 0,038 | 0,043 |
| **OSR** | [$m^2/m^2$] | Open space ratio | 0,111 | 0,129 | 0,130 |
| **PT** | adim. | Planimetric Trend | 7 | 10 | 3 |
| **PTis** | adim. | Planimetric Trend Interruptions | 7 | 10 | 7 |
| | | **Space** | | | |
| **Vd** | [$m^2/m^2$] | Vertical density | 1,91 | 2,05 | 1,30 |
| **VOSR** | [$m^2/m^2$] | Vertical open space ratio | 6,12 | 5,97 | 4,47 |
| **VAr** | [$m^3/m^2$] | Volume-Area ratio | 12,04 | 10,98 | 8,51 |
| **rSA** | adim. | rapport with Surrounding Aggregates | 7 | 10 | 7 |
| **rTM** | adim. | relation to the Territory Morphology | 3 | 7 | 3 |
| **AT** | adim. | Altimetric Trend | 7 | 7 | 3 |
| **MVld** | adim. | Mountain-Valley levels difference | 7 | 7 | 3 |
| | | **Analysis-oriented** | | | |
| **TCl** | adim. | Typological Commingling level | 5 | 5 | 3 |
| **STS** | adim. | presence of Specific Typological Structures | 7 | 5 | 5 |
| **TAd** | adim. | Typological Alteration degree | 10 | 5 | 7 |
| **Sd** | adim. | Stratification degree | 10 | 5 | 7 |
| **SF** | adim. | Sky Factor | 25,2 | 22,0 | 30,2 |
| **SVF** | adim. | Sky View Factor | 21,4 | 19,0 | 24,7 |

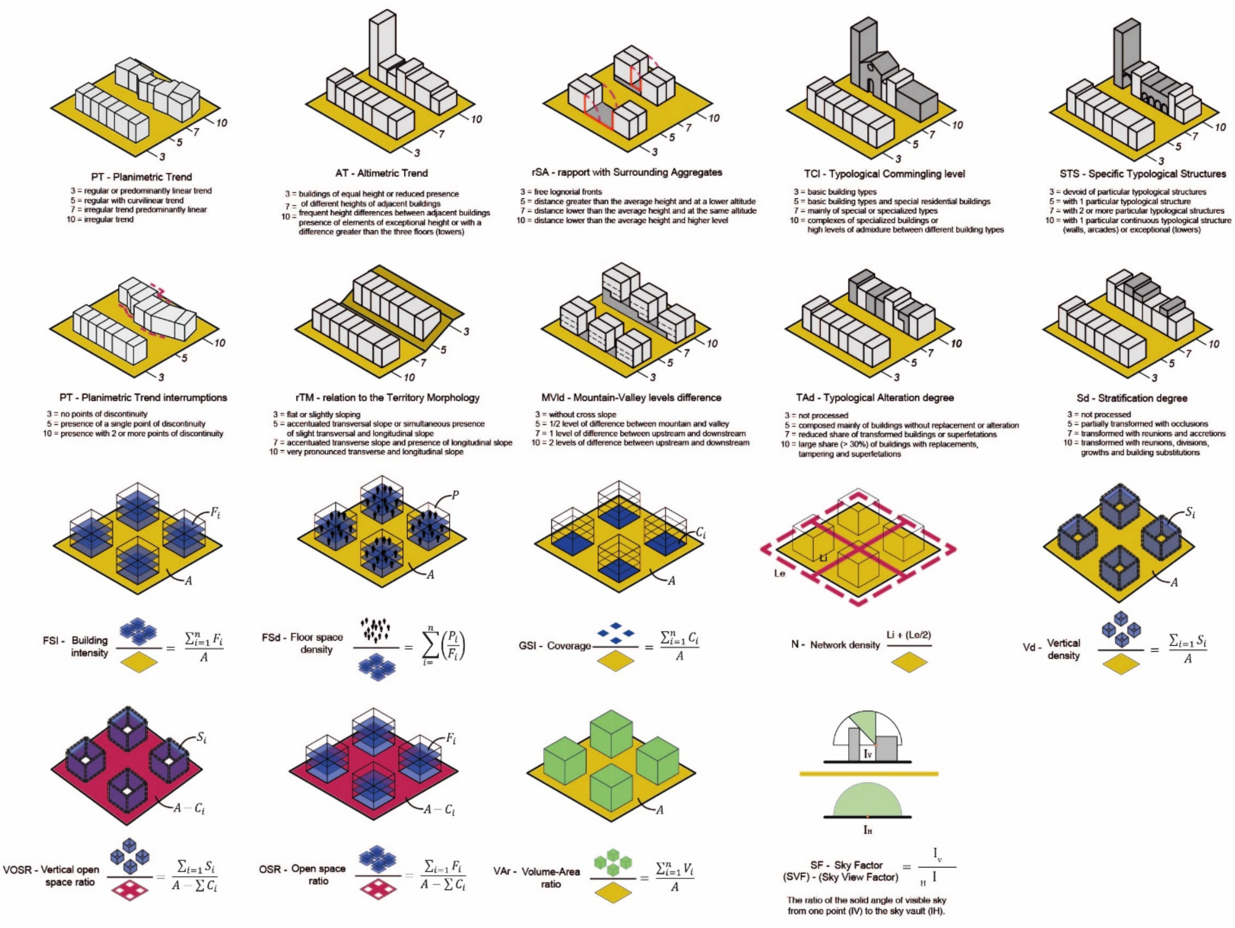


**Figure 2** Description of morpho-typological indicators (MTI) and urban metrics (UM).

**Table 3.** Structural characteristics parameters and total values, TI total values and vulnerability index.

| | I | II | III |
|---|---|---|---|
| Average conservation status of vertical structures | 5 | 3 | 3 |
| Average conservation status of horizontal structures | 5 | 3 | 3 |
| Average state of conservation of the roofs | 5 | 3 | 3 |
| Synthetic index of masonry quality | 7 | 7 | 7 |
| Presence of particular structural elements | 5 | 5 | 0 |
| Offset of floors between adjacent buildings | 7 | 7 | 10 |
| Slenderness of the wall | 3 | 3 | 3 |
| Pushing elements (arches, vaults, roofs) | 7 | 10 | 7 |
| Masonry discontinuities | 7 | 7 | 5 |
| Discontinuities or singular elements in vertical structures | 1 | 5 | 1 |
| Discontinuities or singular elements in horizontal structures | 1 | 5 | 1 |
| Discontinuities or singular elements in roof structures | 1 | 5 | 1 |
| Regularity in the arrangement of openings | 3 | 3 | 7 |
| **Total indicator of structural characteristics** | **57** | **66** | **48** |
| **Total TI** | **70** | **71** | **51** |
| **Overall vulnerability index** | **127** | **137** | **99** |
| **Overall vulnerability index (normalized)** | **8** | **9** | **3** |

**Table 4** Value of solar energy over a one-year period regarded to case studies.

| | Unit | I | II | III |
|---|---|---|---|---|
| Solar radiation | kWh* | 2.748.809 | 2.283.577 | 2.107.196 |
| Façade energy density | kWh/m$^2$* | 269,1 | 320,2 | 369,0 |
| Direct solar radiation | kWh | 662.113 | 550.052 | 507.566 |
| Diffuse solar radiation | kWh | 1.315.029 | 814.776 | 850.469 |
| Global solar radiation | kWh | 1.977.142 | 1.364.828 | 1.358.035 |
| Direct façade energy density | kWh/m$^2$ | 64,8 | 77,1 | 88,9 |
| Diffuse façade energy density | kWh/m$^2$ | 128,7 | 114,3 | 148,9 |
| Global façade energy density | kWh/m$^2$ | 193,5 | 191,4 | 237,8 |
| Direct solar radiation fraction | | 33% | 40% | 37% |

* *Considering cloudless sky condition*

Concerning solar energy, irradiation on façades (kWhm$^{-2}$y) is directly related to a combination of high-density-related values (GSI, VOSR, Vd) and low SF/SVF values. In historical urban textures, reasons for better solar access compared to observed tendencies, are due to specific morphological features: lower urban density combined with optimal façades orientation (**III**). Instead, solar performance is in general poor for cases with high urban density (as described by each UM). Even though similar surface exposure and lower SF/SVF, case **II** receives more solar radiation compared to **I**. This result is reliably represented by UM (FSI, GSI, VOSR and VAr). Comparing fractions of direct and diffuse irradiation for case studies, we notice that differences between **I** and **III** are almost levelled by increasing of diffuse radiation (Table 4). Based on these results, it can be argued that, considering the most reliable metrics for solar analysis as indicated in previous studies [18], **II** and **III** performs better than the average. The former, due to the presence of several courtyards and higher ratios of façade surface/built volume. The latter thanks to favourable texture orientation in relation to façade exposure.

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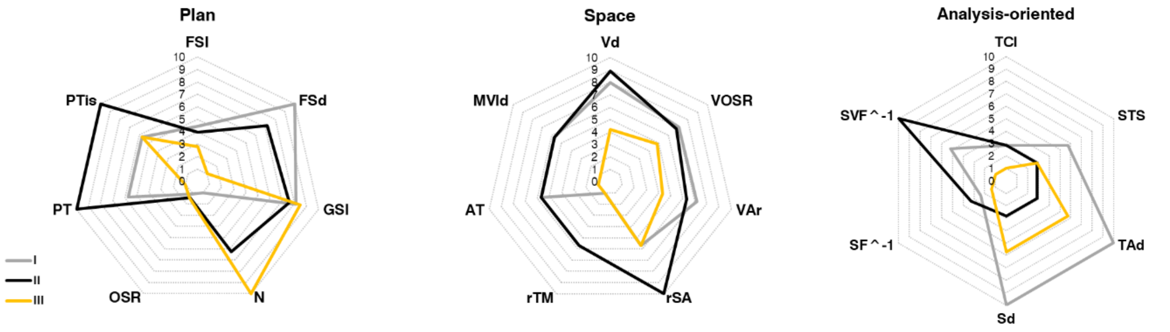


**Figure 3** Comparison of normalized UM and MTI (grouped into Plan, Space and Analysis-oriented)

### *3.2. Urban form metrics and typological indicators*
Table 2 and Figure 3 show respectively the computation of UM and MTI and the corresponding normalized values for case studies (decimal scale). The purpose of the diagrams is to visualize the urban scale performance: the higher the value of an indicator, the worse the behaviour of the aggregate in term of solar availability and seismic vulnerability. For this reason, we use reciprocal value for SF and SVF. In general, to combine different indicators helps clearly understand building density and compactness of urban fabric: compared to cases **I** and **II**, we can observe that case **III** is more compact and have less building intensity, producing openness in the urban form. By grouping different types of UM and MTI is possible to highlight urban form features of each case as shown in Figure 3. Case **III** values clearly reflect differences in urban layout and morphology of the island. Moreover, the difference between **I** and **II** appears: **II** has higher values in most of the *Plan* and *Space* metrics, while **I** has higher values in all the *Analysis-oriented* metrics. The case **I** and **II** are the aggregates with lower performances, while case **III** always covers the smaller areas of the graphs, showing as in a regular urban texture exist more favourable condition.
First-stage evaluation of seismic vulnerability and façade solar availability at urban scale can be obtained making use of the diagrams: the smaller the area on the proposed diagrams, the greater are the intrinsic capacities of the urban aggregate to perform at both levels.

## 4. Conclusion
Our paper presents an investigation on the capability of a multi-criteria analysis based on UM and MTI to predict urban seismic vulnerability and solar availability in the historical city located in Mediterranean climate. The Plan indicators highlight intrinsic criticalities of urban texture regarding the horizontal plan, therefore strictly related to urban form and very hard to transform without invasive action that could compromise the historical value. The Space indicators, due to their three-dimensional definitions are suitable to describe renovation strategies based on urban acupuncture and geometric regularity, taking into account the interaction with the urban surroundings. The Analysis-oriented indicators are suitable to control urban form and typology implications of solar and seismic performance and to improve them through solar and seismic sensitive design.

The proposed multi-criteria analysis model has been structured with several purposes. On one hand, it can support policy maker decisions according to the performances of urban aggregates, in order to differentiate public investments and incentives; on the other hand, it should be integrated in the early stage of design process, taking into account the solar façade availability and seismic vulnerability of urban areas to guide urban renovation strategies.

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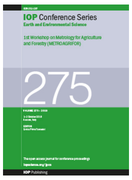


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