A New Methodology for Using Hybrid Configurational Tools for Local Analysis of Pedestrian Flows in Large Areas

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Abstract. In recent years, the concept of sustainable mobility has been increasingly pursued; as a result, the need for effective planning of pedestrian infrastructure is highlighted. This research employs configurational analysis, specifically the spatial syntax methodology, to examine pedestrian flows in urban environments. Spatial analysis was integrated with demographic data to assess pedestrian movement patterns and network accessibility. The area in question falls within a district of the city of Rome, such as the Nomentano-Tiburtina. To improve predictive accuracy, an approach is proposed that studies the influence of neighboring municipalities on the estimation of pedestrian crowding. The results reveal that this consideration significantly influences the integration and estimates of pedestrian flow. This study offers valuable insights for urban planners seeking to optimize pedestrian networks and promote sustainable urban mobility.

Keywords: Sustainable mobility · Pedestrian · Space Syntax · Configurational approach

1 Introduction

Sustainable mobility refers to a mode of transport and movement that is responsible and has minimal environmental impact. It includes a set of virtuous mobility practices that can bring environmental, social, and economic benefits. Thus, not only does the environment benefit from this alternative mobility, but also the entire population experiencing it.

The issue of managing sustainable transport modes has become one of the most debated issues in recent years within local, national, and international environmental policies aimed at reducing the environmental impact from the movement of people and goods. Improving the environmental aspects of mobility demand, particularly in urban areas, is a priority to promote a better quality of life for citizens. This includes social and cultural relationships, as well as the health benefits of increased physical activity and the creation of new economic and development opportunities. Furthermore, if walking or

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cycling becomes an alternative to motorized transport, it improves the urban environment by reducing emissions, whether in terms of noise and air pollutants or fine particulates in the atmosphere, congestion of vehicles (measured by the time spent by motorists in traffic to cover the same distances), and allows greater usability of public spaces within the urban fabric.

In recent years, also due to the pandemic emergency, especially in urban areas, citizens' habits have changed. They preferred alternative methods for their trips to keep the distance and move safely, with walking or cycling among the most interesting options. This has led administrations to reorganize urban areas to make them attractive but also safe for users.

However, this increase in pedestrian mobility has led to increased exposure to the risk of accidents [1], whose exposure can be defined as the annual number of vehicle-pedestrian collisions divided by the estimated annual volume of pedestrians at a given intersection [2, 3]. It is therefore necessary to assess the pedestrian congestion and its routes and understand what the main risks are that these vulnerable users face in order to be able to address them. The study of pedestrian congestion involves first going to investigating the pedestrian network and its shape.

In the literature, this is often investigated by means of "proximity" models implemented with a specific algorithm in a QGIS plugin called Space Syntax [4–9]. Among the descriptive parameters of the model, the one investigated in this research is the Integration, which describes the probability that each section could be chosen or not by the pedestrian to carry out the movement from a point of origin to a point of destination.

However, previous studies have shown a weak correlation between Integration and real pedestrian flows [10–12], obtaining low correlation coefficients ranging from 0.2 to 0.4. It is in this context that numerous studies have shown how network connectivity affects pedestrian activity, but not only, other variables such as population, land use, purpose of travel, and means of connection also affect the behaviour of pedestrians [13–15]. A recent literature review [16] has shown that most studies focus on high-density urban areas and limit themselves to the pedestrian network configuration analysis, without integrating socio-demographic or contextual factors.

In addition, there is little detail on issues such as pedestrian congestion, flow volume management, and the influence of surrounding areas on pedestrian behaviour.

So, the possibility of introducing population weight to identify the right configuration parameters could be an approach that leads to an improvement of the model [17–20]. This research therefore proposes to use a hybrid approach, developed on a real case study, combining configurational analysis with a proximity model based on population density, evaluated by means of concentric buffers with increasing radius.

Not only, among the parameters that influence the assessment of pedestrian crowding, especially in large-scale areas, was investigated the influence of the areas surrounding the case study area [21, 22].

A methodology has been developed that allows not only the assessment of pedestrian crowding through proximity methods with the use of Open-Source GIS software but also a methodology to identify the portion of area bordering the area of the case study to be considered in the development of the hybrid approach described, to achieve results that are as close to reality as possible.

2 Vulnerable Users of the Road

In the panorama of urban mobility, the pedestrian component is certainly fundamental, but at the same time is considered weak.

Even if sustainable mobility is a widespread and consolidated concept, the pedestrian's aspect remains marginal compared to other transport policies, because, to walk, little space is needed, no infrastructure, no organization, and no means. It is also well known that walking is always possible within a generic urban environment, and therefore, it is not necessary to deal with the studies associated with it in depth.

In the organization of public services, people have mistakenly become accustomed to thinking in terms of supply, so that pedestrian mobility does not seem to need anything to be developed, being perceived as a sort of "natural" endowment deriving from urbanization, which does not necessarily imply accurate planning, projects or specific resources.

The lack of disciplinary and political attention to pedestrian mobility greatly undermines its proper development. Outside the historic centers and in the suburbs, the space reserved for pedestrians, or in any case intended for means of transport other than vehicles, tends to reduce to a minimum, inevitably losing quality and in some cases reaching to be physically not feasible or difficult to use for part or the totality of potential users.

According to ISTAT in Europe [23], 30% of journeys by car cover distances less than 3 km and 50% less than 5 km; such movements could be easily completed in 15–20 min with cycles or 30–50 min on foot. It is clear, therefore, that the conversion of a significant proportion of car journeys to walking or other means an alternative to motor vehicles is not only desirable, but also possible, to benefit also from the increasing rates of sedentariness and for the reduction of accidents concerning the pedestrian fraction of road users, equal to 485 deaths only during 2022, increasing compared to previous years.

3 Methodology

To obtain a model of pedestrian flows, the methodology shown in the following flow chart has been implemented (see Fig. 1).

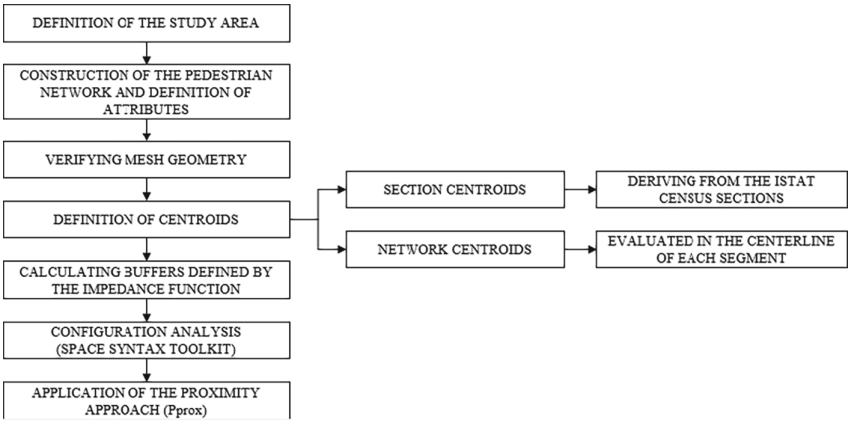

Fig. 1. Flow chart of methodology.

The study of pedestrian crowding using Spatial Syntax includes a configurational analysis that is independent of factors such as emissions or modal choice, focusing solely on the shape of the network. This approach is influenced by the historical development of urban areas, where city centers typically consist of dense and interconnected road networks.

Between key indicators used in this analysis includes the *connectivity* that is a local measure indicating the number of elements directly linked to a space; the *choice* that reflects the flow of movement through a space, with higher values associated with shorter pathways connecting multiple areas; the *integration* that is a global measure of accessibility, representing the minimum number of steps required to reach a point from another within a graph.

Integration thus makes it possible to assess the probability that a place will be chosen as a destination by users [10]. This is particularly relevant in urban contexts where pedestrian flows are strongly influenced by the distribution of destinations, services, and housing densities. Several studies see the use of the integration variable to run it on pedestrian flows in different contexts [10–12, 19, 24].

Various mathematical formulations exist to calculate integration, with the method proposed by Raford and Regland [1] being commonly used (see Eq. 1).

$$INT = \frac{2(MD - 1)}{K - 2} \tag{1}$$

where:

- MD is the Mean Depth of the entire system; it is the measure that indicates, starting from a specific point, how many road segments on average are needed to reach all other points of the network [4].
- K is the number of nodes in the network.

Since a purely configurational approach does not seem to reflect the complexity of urban pedestrian behaviour, this study proposes a hybrid methodology combining spatial syntax analysis with land use data. This integration aims to improve the accuracy of pedestrian flow forecasts by incorporating both spatial and functional aspects of the urban environment.

The analysis in this study comprises two main phases. Initially, it was established road and pedestrian networks by establishing spatial connections between census sections and road segments. To attribute population values to network segments, obtained from the Italian National Institute of Statistics (ISTAT) databases [25], a proximity approach is used. This method links the attributes of each network centroid (i.e., the midpoint of each road segment) with surrounding centroids using a series of buffers with increasing radii. The radii of these buffers range from 100 to 1600 m, determined by an impedance function [26] that describes pedestrians' likelihood to travel as travel distance varies (see Eq. 2).

$$P_{prox,i} = \sum_{j=100\ m}^{1600\ m} k_{Mj}\, M_{ij} \tag{2}$$

where:

– k_{Mj} is the propensity to perform a trip;
– M_{ij} is the average population value.

In the initial phase, it was determined a weight, denoted as P_{prox}, was determined for each network centroid. This weight was calculated at increasing distances from the individual centroid, considering the actual propensity of users to move as their distance from it increases. The objective was to establish a weight factor representing the attractiveness of pedestrian flows, based on the average population residing in the specific circular crown area for each road segment.

Subsequently, in the second phase, configurational analysis was conducted within the Space Syntax framework. It was conducted that both "weighted" and "unweighted" analyses were conducted to evaluate the effectiveness of the new "hybrid" approach in comparison to a conventional configurational analysis in predicting pedestrian flows in a real urban setting. In the weighted analysis, the respective P_{prox} values are associated as attributes to the network segments, it will be possible to use them as weights in the predictive analysis with Space Syntax.

4 Case Study

The study area on which this research focuses is located in central Italy, in particular in an area of the metropolitan city of Rome (see Fig. 3) that includes Municipality 2 (see Fig. 2).

The study area (see Fig. 3) includes the zones of Nomentano–Tiburtino located within Municipality 2 of the metropolitan city of Rome.

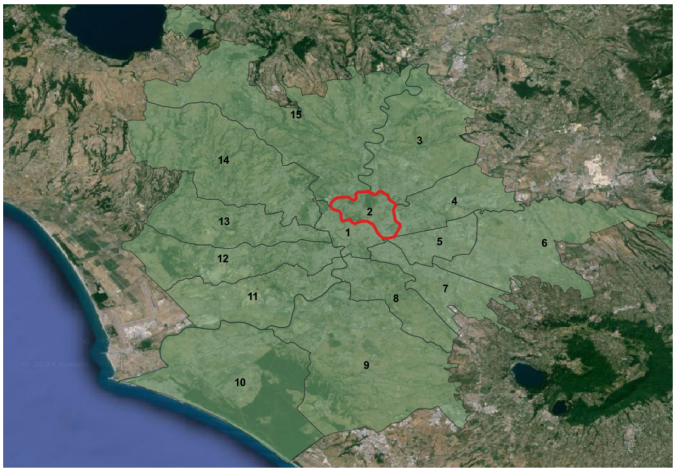

Fig. 2. Municipalities of the metropolitan city of Rome (in red the Municipality 2 under study).



Fig. 3. Case study area (in blue) located in Municipality 2 (in red).

This area sees the presence of metro stations, the proximity to the Roma Tiburtina station, the presence of the University of Rome "La Sapienza", and the Polyclinic "Umberto I". This makes it an area of strong pedestrian attraction, where it becomes crucial to analyze pedestrian flows and the related pedestrian network in order to highlight any disconnections present and provide for their resolution.

4.1 Analysis of the Results

The study area was divided into census sections, each having a centroid as its representation. Following the transfer of population information from section centroids to network centroids, proximity weights (P_{prox}) were assigned to network segments. Subsequently, the hybrid forecasting analysis was initiated. This approach was adopted due to the

observation that the pure configurational approach failed to fully capture urban pedestrian activities. Hence, a hybrid method integrating Space Syntax-based configurational analysis with land use and pedestrian travel behavior was proposed.

The results, categorized based on the type of weight used, are displayed on the screen along with corresponding chromatic representations of the network (see Fig. 4 and Fig. 5).

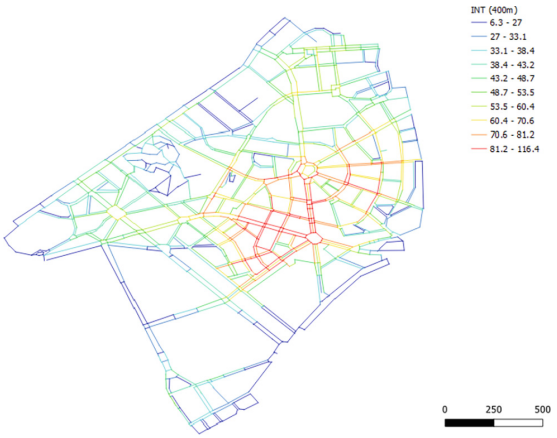

Fig. 4. Configurational analysis (unweighted) of the pedestrian network.

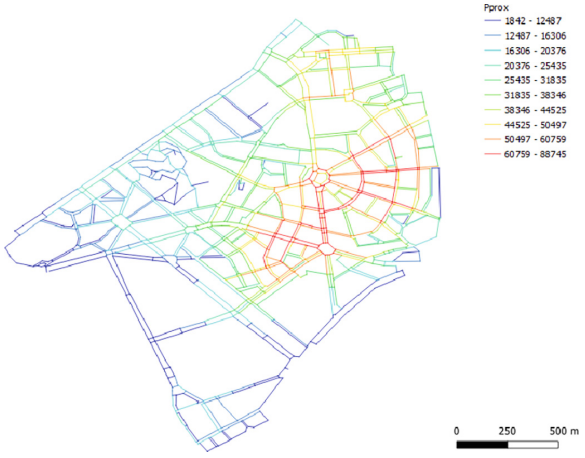

Fig. 5. Configurational analysis (Proximity weight) of the pedestrian network.

Both analyses lead to almost similar results, the substantial difference is that in the unweighted analysis (see Fig. 4), the most loaded sections of the pedestrian network are the most interconnected and belong to the Central Business District (CBD). In the analysis weighted with the weight of proximity (see Fig. 5), interacting the geometric

component with that relating to the population and the willingness of pedestrians to move, it can be seen that the central area still has high integration values, in particular the area where there is the metro station and in the vicinity of the Roma Tiburtina station.

In this case, the peripheral area at the top also has high Integration values, probably because this area has a high resident population that generates more trips.

In order to determine the configuration of the pedestrian paths, the areas with and without the presence of sidewalks (see Fig. 6) and the uneven areas in the network due to missed pedestrian crossings (see Fig. 7) were detected. Because of these areas, pedestrians tend to cross in an "abusive" and therefore unsafe way, increasing the risk of accidents, and this could lead the pedestrian to give up following this path and perhaps prefer the car and/or other modes of transport to travel it.



Fig. 6. In red, the sections of the pedestrian network where there are no sidewalks.

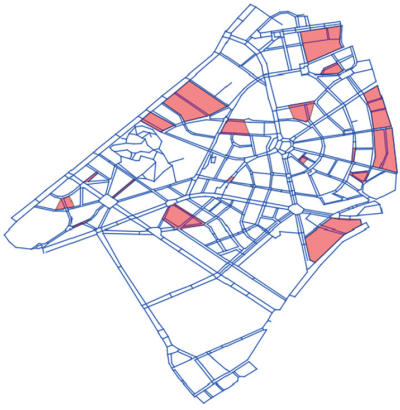

Fig. 7. Disconnected areas (in red) in pedestrian paths due to missed crossings.

4.2 Configurational Analysis of the Case Study in Relation to Neighboring Areas

In order to study the behavior of pedestrian flows influenced by the areas bordering the area of the case study, the construction of the pedestrian network was extended to Municipalities 3 and 4 (see Fig. 8).



Fig. 8. New study area conveying the case study area and Municipality 3 and 4.

A configurational analysis was carried out of the new pedestrian network, comparing it to the one in the case study, described above, and those of Municipalities 3 and 4.

In Fig. 9 is possible to see the configurational analysis result expressed by the Integration indicator.

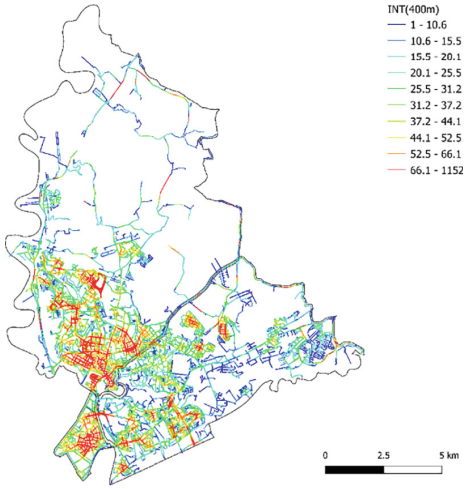

Fig. 9. Values of Integration that combined the Nomentano-Tiburtina pedestrian network between the neighboring Municipalities.

In Fig. 10 is possible to see the configurational analysis result expressed by the P_{prox} weight indicator.

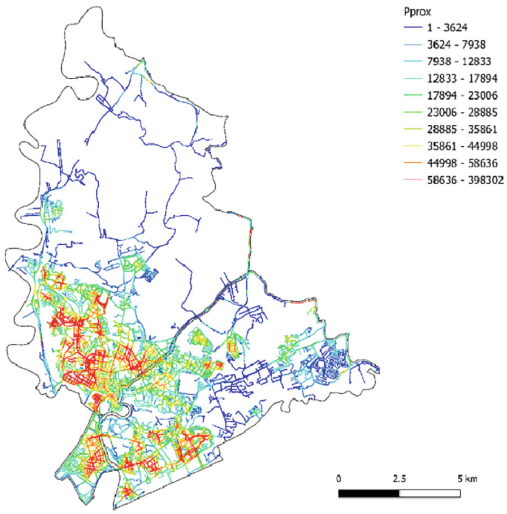

Fig. 10. Values of P_{prox} that combined the Nomentano-Tiburtina pedestrian network between the neighboring Municipalities.

In order to be able to evaluate any differences between the indicators obtained from the configurational approach applied only to the Nomentano-Tiburtina area and those

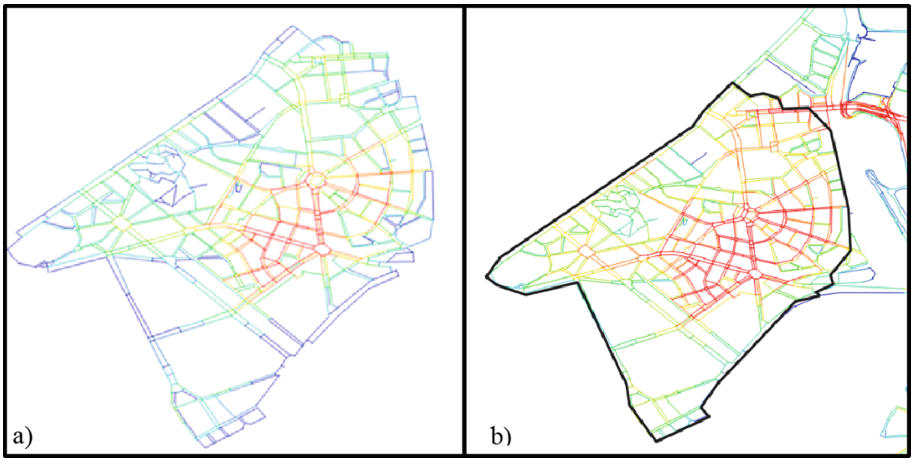

Fig. 11. **a)** Values of Integration Indicator without the influences of the neighboring Municipalities. **b)** Values of Integration Indicator that combined the Nomentano-Tiburtina pedestrian network between the neighboring Municipalities.

obtained also considering the neighboring municipalities, a focus is carried out on the study area (see Fig. 11 and Fig. 12).

In Fig. 11 and b, it is possible to see the comparison, in terms of Integration Indicator, of the two cases analyzed.

What can be seen is that the presence of the neighboring municipalities greatly influences the values of Integration because, as can be seen in Fig. 11a, they are much stricter than those obtained for the Nomentano-Tiburtina area alone, not considering this influence. In particular, in the vicinity of the border between the Nomentano-Tiburtina area and the Municipalities III and IV of Rome, the values of Integration are strict. This is probably due to the influence of these neighboring municipalities, which have an estimated high pedestrian turnout in these areas. The same comparison was made in terms of P_{prox} (see Fig. 12a and b). Also in this case, the influence of the neighboring municipalities leads to an increase in the aforementioned indicator, but in a more modest way.

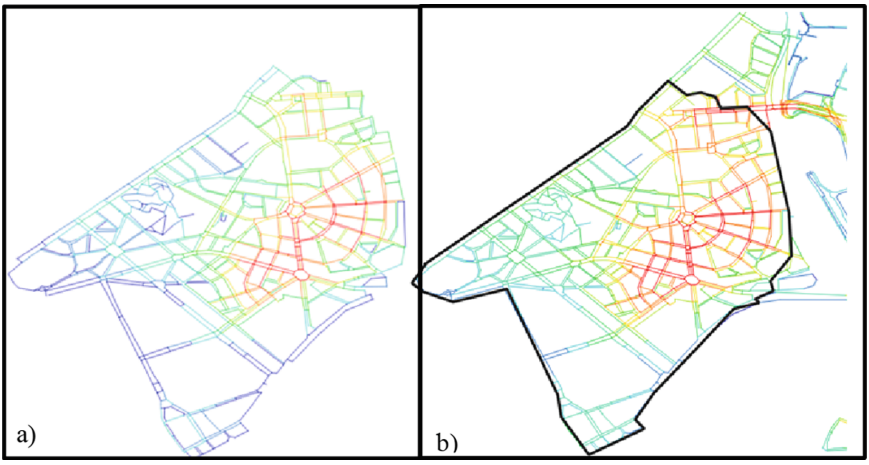

Fig. 12. **a)** Values of Pprox weight Indicator without the influences of the neighboring Municipalities. **b)** Values of Pprox weight Indicator that combined the Nomentano-Tiburtina pedestrian network between the neighboring Municipalities.

In order to define how much the presence of neighboring municipalities influences, in terms of results, the correct Integration values were related to the weight of proximity, considering only the Nomentano-Tiburtina area, and also considering the neighboring municipalities.

As can be seen from Fig. 13, there is a differentiation of the Integration values in the two configurations, reaching a Pearson of 0.8.

By virtue of this, an in-depth study was carried out, considering only the portion of the pedestrian network within the study area, leaving out the external cordon that connects the Nomentano-Tiburtina with the neighboring municipalities. To determine the extension of the pedestrian network of the Nomentano-Tiburtina district that is not affected by the influence of neighboring municipalities, progressive buffers of 20 m

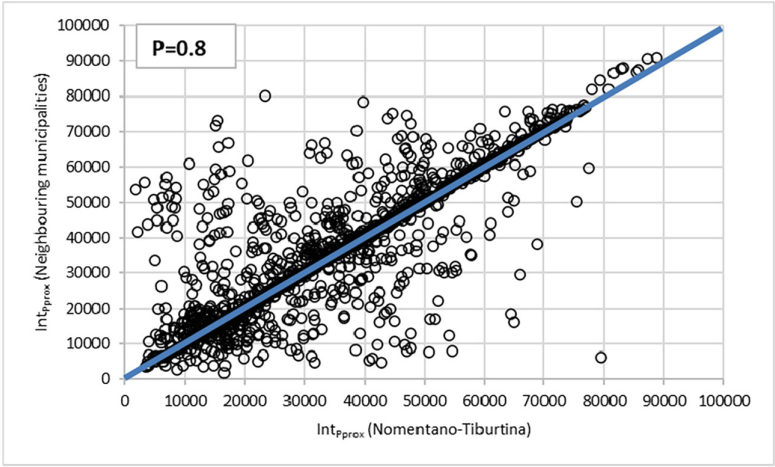

Fig. 13. Relationship between Int_{Pprox} considering only the Nomentano-Tiburtina area and on the other hand, also considering the neighboring municipalities.

were generated towards the interior of the area. With each iteration, the portion of the pedestrian network outside the buffer is subtracted, progressively redefining the study area. To assess the consistency of the process, Pearson's correlation coefficient was calculated at each step. The iteration was interrupted when the Pearson value reached about 0.9, indicating that the external influence is negligible and the portion of the network considered is statistically representative of the study area.

Figure 14 shows the relationship between the value of the Pearson correlation coefficient, calculated at each iteration of the process described above, and a dimensionless term introduced to quantify the effect of the progressive reduction of the area considered. This term has been defined as the ratio between the radius representing the area of the portion subtracted through the application of buffers (r) and the original radius of the study area (R). The trend of the relationship illustrated in the figure allows us to highlight how the variation of the spatial extension affects the correlation, providing a quantitative criterion to determine the threshold beyond which the influence of neighboring municipalities becomes negligible.

What can be deduced from the trend in Fig. 14 is that in the initial phase, there is a strong reduction in the Pearson value, indicating that the pedestrian network near the boundary of the study area is influenced by the presence of neighboring municipalities.

However, for values of the r/R ratio less than about 0.5–0.6, the variation of the Pearson coefficient becomes less pronounced, suggesting that the effect of neighboring municipalities is progressively reduced until it becomes negligible. The iterative process was interrupted when the Pearson coefficient reached the value of 0.91, as this threshold represents a good compromise between the elimination of external influence and the preservation of a statistically significant study area.

The analysis, therefore, confirms that the progressive reduction of the study area makes it possible to mitigate the effect of external conditions, stabilizing the correlation

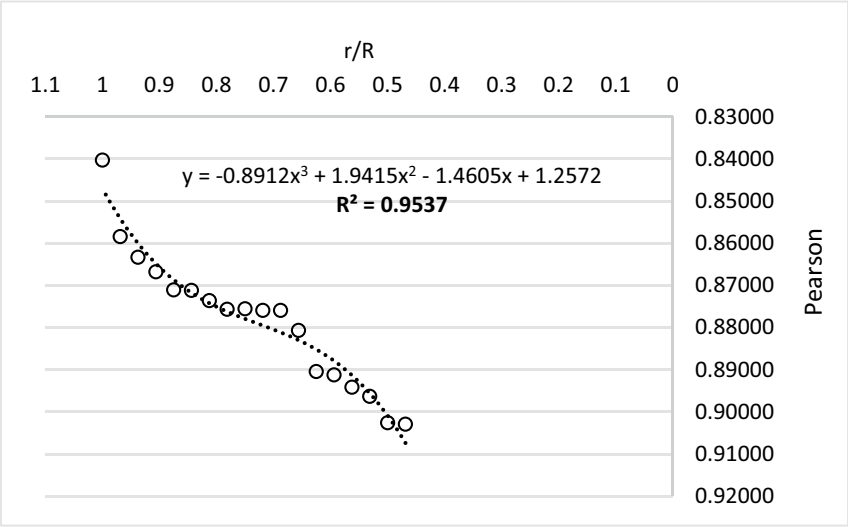

Fig. 14. Pearson's trend concerning the progressive reduction of the area considered

and making the analysis of the pedestrian network in the Nomentano-Tiburtina district more robust.

The portion of the area that identifies the best Pearson is represented in Fig. 15.



Fig. 15. Area of the Nomentano-Tiburtina pedestrian network that is not affected by the presence of neighboring municipalities.

Therefore, the correlation between the Integration values corrected with the proximity weight considering the presence of neighboring municipalities and the Integration values corrected with the proximity weight considering the Nomentano-Tiburtina

pedestrian network subtracted from the portion of the area defined above is shown in Fig. 16.

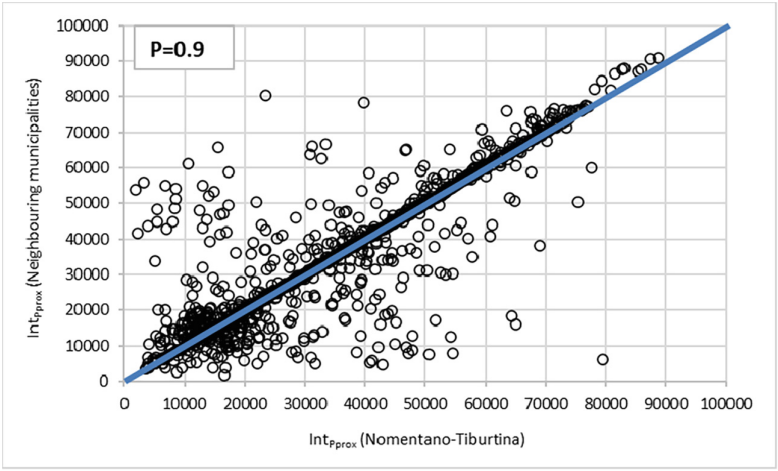

Fig. 16. Relationship between Int_{Pprox} considering only the Nomentano-Tiburtina inner area, and on the other hand, also considering the neighboring municipalities.

This implies that the presence of neighboring municipalities influences the external cordon of the study area, i.e., the one soon to communicate with them.

5 Conclusion

To encourage the adoption of soft mobility, it is necessary to integrate cycle and pedestrian paths into urban projects, ensuring that they are well-designed and convenient for users. It is important to understand the needs of the population and to create a network of connections that is efficient and accessible. To adequately size these routes, it is essential to analyze the flows of people and their movements in the urban context. An innovative approach to estimating pedestrian displacements was developed. However, further experimental validation is needed to refine this model. This approach could be invaluable for city administrators, allowing them to assess and mitigate risks related to road safety and pedestrian traffic by integrating data on pedestrian activities with information on vehicular traffic.

The analyses carried out showed that the presence of neighboring municipalities has a significant impact on the values of Integration and P_{prox} in the Nomentano-Tiburtina area. When considering these neighboring areas, the integration values become considerably stricter, probably due to the higher pedestrian influx influenced by neighboring municipalities. Similarly, P_{prox} values also increase, although to a lesser extent, indicating a modest influence of neighboring areas on this indicator. These findings underscore the importance of considering broader geographical contexts in urban planning and analysis to accurately assess and address various urban parameters and dynamics.

In particular, it has been demonstrated that the presence of these areas influences the results obtained in terms of Integration in a particular area of influence or the area immediately bordering the adjacent areas. As far as the "internal" part of the study area is concerned, it presents a strong agreement between the configurational analysis conducted without the presence of the neighboring municipalities and with the presence of the latter. This leads to say that, as far as the development of configurational analyses of large areas is concerned, it is necessary to consider an "internal" area that is not affected by the influence of confined areas, which, on the contrary, have a strong impact on the cordon area near the latter.

A potential limitation of this study concerns the use of topological buffers as reference areas for pedestrian density estimation.

Although this approach is effective for general modelling of proximity, it does not take into account travel speeds influenced by various factors such as land use or infrastructure quality [27]. The literature also shows that informal links are often used by pedestrians and significantly influence real movement patterns [28].

In the future, it is planned to extend the modelled pedestrian network by integrating it with other informal links and to consider speed of travel and quality of pedestrian infrastructure as additional variables influencing the results on pedestrian congestion.

What is more, this research aims to be able to assess whether and how the presence of shops can influence the assessment of pedestrian traffic, and it is also planned to calibrate the model with a collection of pedestrian flow data.

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