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A topological analysis of Milan historical surface transport networks from 1856 to the present

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ABSTRACT

This research examines the transport networks operating in Milan, Italy, in seven years, from 1856 to 2016. The networks are transformed into graphs and analysed with several techniques from graph theory, including a new centrality index called Icentr. With the help of this index, we identify the nodes, to be considered primary in the transportation network, that are better related both in terms of topology and more interconnected in terms of distance. The findings provide a detailed picture of how the primary nodes have shifted from the city's inner core to outer areas over the course of the investigated decades, both for the topological case and when the graphs are weighted based on the distance between nodes. Particularly, the effect of distance is more evident in those historical phases when the city expands, creating longer connections between nodes, in contrast to phases when the city becomes denser. The proposed method of analysis appears suitable to be applied to other cities, both for simplicity and effectiveness.

Introduction

Urbanisation in the last century and nowadays is the outcome of a natural increase in people for new births, emigration from rural areas and from abroad,

Each city has its own process of development, both for urbanisation (first process) and for transportation network (second process) technologies, leading to different combinations of urban forms, spatial structures, and transportation systems. The book by Rodrigue (2020) can be relevant for additional information on these subjects. Basso et al. (2021) propose a model to study urban regulations and transport policies in the long run.

The evolution in time of the two processes and of their relationship can be analysed at different time scales (short, medium, and long) according to the aims. Of course, a long-term analysis forces in some way to aggregate variables, and it seems more suitable from an historical perspective and to get insights for modelling the two processes; a short-term analysis seems more suitable in the case the two processes are to be controlled and managed at the present.

Many papers analysed the relationship between the two processes, but few also from a historical point of view. Among these, the paper by Yu et al. (2023) analyses the spatiotemporal growth patterns of metro networks from three dimensions, i.e., accessibility, resilience, and serviceability. The urban metro network may develop as a response to the city's needs hierarchically, from the most basic (e.g., accessibility) to the most advanced (e.g., resilience and serviceability). The paper by Huang et al. (2014) studies the spatio-temporal evolution of the rail network in Guangzhou (China) for four years in an interval of 12 years using complex network theory. It focuses on the relationship and interaction with the bus service system and the overall improvement of urban accessibility. The influence of regional rail transportation infrastructure on employment and population growth in the Paris metropolitan area between 1968 and 2010 is analysed by Garcia-López et al. (2017). The spatial–temporal relationship is also analysed in Aljoufie et al. (2011) for the city of Jeddah (Saudi Arabia) from 1964 to 2007 by using socioeconomic indices.

Rather than modelling the aforementioned process of the dynamics between population and urban growth on the one hand, and the growth of transport services on the other, this study intends to propose a new approach to reporting and analysing its evolution from the transport point of view. Considering all the various aspects that make up that process, it is not an inconsequential issue. Even though certain context descriptions are given from that perspective to round out the framework, the analysis is not urbanistic.

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Afterwards, we concentrate on the examination of the historical maps of Milan surface transport networks from 1856 to 2016, which, when transformed into graphs, can be studied through graph theory tools. In fact, the analysis hinges on the application of the centrality index, Icentr, which allows us to identify the most relevant nodes of the graph (Mussone et al., 2022). As will be elucidated in the sections that follow, in this case, 'relevant' stays for 'best connected' with all the other parts of the graph.

There are five more sections developed in the paper. An analysis of the attributes of the graphs created from the historical maps of transport networks is done in Section 2. The centrality indices, specifically the one employed, are explained in Section 3. Section 4 describes the adopted methodology and reports the outcomes of the application of the centrality index. In Section 5, the results are discussed, and in Section 6 the conclusions are drawn.

The historical maps of Milan surface transport networks and their graphs

The transportation maps

Far from being a historical paper, this research has considered six maps of historical arrangements of surface transport networks in Milan, besides one for the current configuration.

The seven maps, reported in Fig. 1, refer to the following years in Table 1 (the city surface is in square kilometres at the closest date of the map from municipality website [Comune di Milano, Censimenti storici, 2024]):

Thorough descriptions of historical reviews about urbanistic processes in Milan can be found in (Iosa, 1971; Campos Venuti et al., 1986; Oliva, 2002; Boatti, 2007; Tucci, 2011).

The factors shaping the urban evolution process are numerous and vary from city to city, making cross-city comparisons increasingly challenging. Specifically focusing on Milan, the primary elements influencing its development include economic drivers and the need for new land for industrial and infrastructural developments outside the existing urban area. Although it is a summary, the following historical account of the city's changes over the decades identifies the key players and factors that contributed to its evolution:

- constructing long-distance transit systems;
- growing industrial communities;
- drawing people from rural areas;
- legally extending municipal boundaries;
- urban plans intended to increase the city's size;
- after-war reconstruction requirements.

These factors have primarily directed the city's expansion and the subsequent growth of its transportation network. Implementing numerous planning policies, starting with Cesare Beruto's plan in 1889, has had a considerable impact on Milan's urban development. These regulations limited the city's growth and created the grid system of Milan's road network, which still has an impact on the transportation design of the city and has a spider web pattern. Furthermore, these characteristics are specific to Milan.

The first map, dated 1856, offers a glimpse into Milan's transportation system shortly before the Italian unification. At that time, Milan was still enclosed within the Spanish walls, with its characteristic heart-shaped layout. The focus of development was the introduction of railway lines, particularly those connecting Milan to Venice and Monza.

Moving forward to 1904, the second map reflects the ongoing transformations in Milan. Favourable reforms and economic conditions led to the development of a robust technical industrial core, with the city expanding towards Monza, Rho, and along the Milan-Venice railway line. Expansion primarily followed major infrastructure corridors, such as railways, although in an unregulated manner until Cesare Beruto's urban planning interventions in 1889.

By 1914, Milan underwent significant expansion, especially with the implementation of the Pavia-Masera urban plan in 1910. Public transportation networks began adapting to the city's growing needs. Even while the maps from 1904 and 1914 seem to be rather similar, upon closer inspection of their graphs' features (which are discussed in Table 2 of the ensuing Section 2.2), we can claim that they are not.

The 1937 map depicts Milan's growth during the interwar period, driven by industrialization and urbanization processes. Public interventions in housing and infrastructure, along with the development of landmark structures like the Politecnico di Milano, characterized this era. Expansion trajectories remained consistent, influencing the development of public transportation lines.

In 1959, the rapid expansion continued in the post-World War II epoch, with significant rebuilding efforts and densification of transportation lines, particularly in outer areas. However, by 1975 and 2016, expansion slowed, and the focus shifted to the redevelopment of existing built-up areas. The closure of industrial sites prompted new developments and increased density, leading to the expansion of public transport networks, including the introduction of new mass transportation systems like the metro.

The graphs

Each graph is built by assigning a node to each crossroad in the network and to each terminal. Nodes are then connected by edges accordingly. The transport service's stops are actually of greater relevance to us, but obtaining this information for the earliest map is somewhat challenging.

Table 2 synthesizes the characteristics of the graphs built from the historical maps. As it can be easily noted, the number of nodes increases progressively by year, from 39 in 1856 to 797 in 2016. In the same way, the number of edges increases by year, but the ratio between the number of edges and the number of nodes is around 1.45. until the year 1937 and around 1.58 until the year 2016. The diameter (the longest shortest distance between whatever two nodes) monotonically increases as well if measured in terms of the number of nodes, but it shows some nonlinear behaviour, being lesser than expected, for the years 1914 and 2016 if measured according to the length of edges (in metres). The ratio between the number of nodes and the diameter (in number of nodes) increases as well, but much less than for the diameter: it goes from 4.33 for the year 1856 to 18.53 for the year 2016, meaning that the increase in the number of nodes is more slightly followed by the increase in the shortest path. In other words, the development of the network has been directed more towards increasing internal connections than expanding the suburbs. This is further confirmed by analysing the values both of the diameter in metres, which increase much less and, in the case of the years 1914 and 2016, even decrease, and the values of the average degree, which increase over the years until stabilizing to 3.2 after the year 1959, which is the post-war period.

The 2016 graph's layout is shown in Fig. 2, where the barycentres of each graph and their distances from Milan Cathedral, from 1856 to 2016 are drawn. The computation of the barycentre coordinates involves merely averaging the coordinates of every node in the graph, without the use of weights. The standard deviation is computed both for x and y coordinates using the same numbers and used as the axes of the nearly nested ellipses in the same Fig. 2; unique exception is the year 1856. One could argue that the monocentric city framework could be used because Fig. 2 indicates that the city barycentre has not changed considerably over the past 150 years (differences are around a few hundred metres). What is worth noting is that these barycentres are quite far from the civil/political centre of the city, which is the Milan Cathedral; the distance is in the order of 2 km for 2016. The subsequent analyses will indicate instead that, already in the map of 2016, more centres are still placed circularly with respect to the historical barycentres.

Additional investigation has been conducted to describe the graphs'

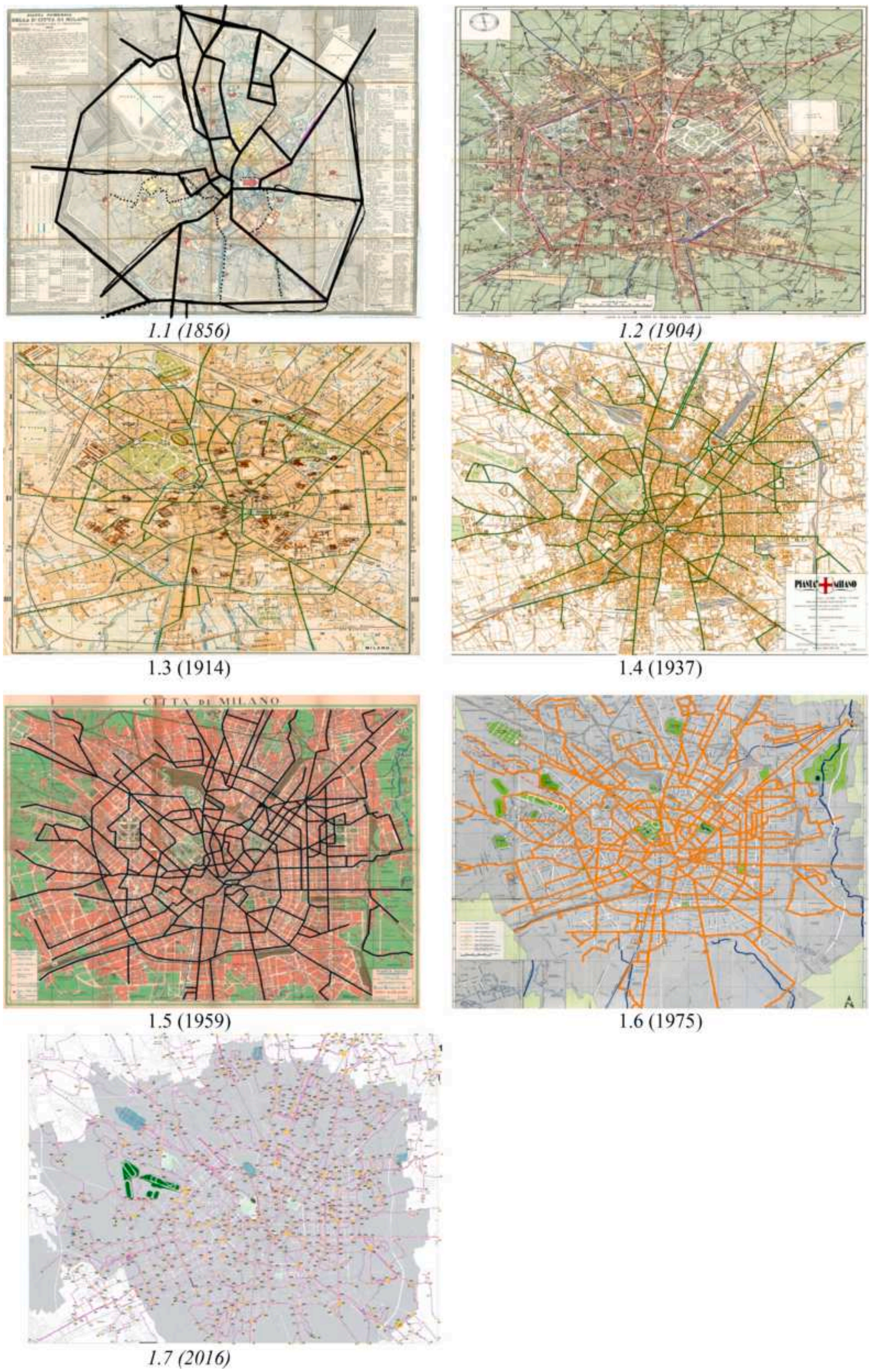

Fig. 1. (1–7) The seven maps used for the study.

Table 1
Years of considered maps and corresponding city surface.

Year	Surface [km^2]
1856	9.7
1904	74.0
1914	76.0
1937	187.0
1959	181.8
1975	181.7
2016	181.7

structure and historical development, as depicted in Fig. 3. Each graph has a curve that, by altering the circle radius from 0 up to the maximum radius encompassing all nodes, reports the normalised sum of edge lengths linking nodes included in the circular area around the barycentre of node coordinates. To interpret the figure, consider that the graph is more expansive (radially more extended) when the curve is convex; in other words, the edges of the graph are longer and sparser in the outside regions. Conversely, when the curve is concave, the peripheral region is denser (the graph is more 'circular'). Flat segments on the curve indicate that, in the area delimited by circles of consecutive radii, there are no nodes.

The graphs of 1856 and 2016 exhibit two limit cases between radial and circular shapes, as Fig. 3 makes evident; the other curves reflect intermediate circumstances. Principal variations in increases towards radial expansions are between 1904 and 1914, and 1914 and 1937.

Centrality index

Centrality index review

Applications of centrality indices (CI) in transportation networks are ubiquitous, and, because they are not the focus of this paper, here we quote only some relevant contributions.

The basic centrality indices are Degree, Closeness, Eigenvector and Betweenness centrality. Degree and Eigenvector centrality measure the attractiveness of each node from a topological point of view. Betweenness and Closeness are based on shortest path computation between all couples of nodes in a graph (Freeman, 1978).

Derrible and Kennedy (2011) recognized that graph theory can be a tool to give a solution to urban transportation problems. Later, Derrible (2012) proposed simplifications to represent the structure of transportation systems.

Street centrality is obtained through the application of Closeness, Betweenness, and Straightness centrality indices. Straightness index measures the connectivity between two points: the more straight the connection, the better the path. Tsiotas and Polyzos (2015) introduced a centrality index called "Mobility Centrality" for analysing traffic flow in a road transportation network through the measure of the propensity of each node to attract network flow.

Chopra et al. (2016) presented a multi-pronged framework that analyses information on network topology, spatial organization and passenger flow to study the resilience of the London metro system. Guo and Lu (2016) proposed to apply the Neighbourhood Centrality, which aggregates the network centrality values in a geographic area.

Kumar et al. (2019) proposed a method to account for the most critical links considering daily functionality of the network, such as evacuation planning and emergency operations, when the closure of even one critical link can alter the whole circulation pattern significantly. They consider three factors for a criticality indicator: the link

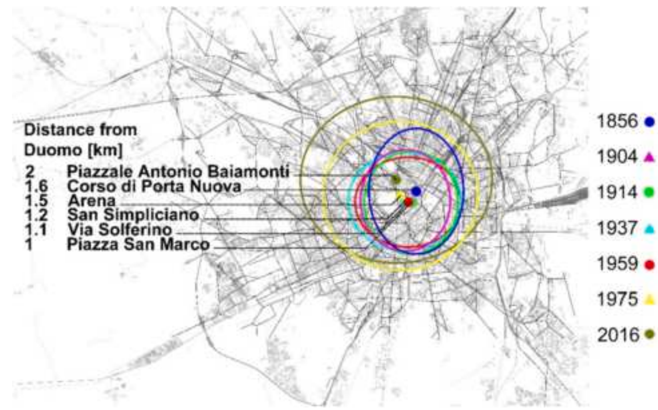

Fig. 2. The barycentres of the considered graphs with the related standard deviation ellipses (in the legend.at left the distance in kilometres of each barycenter from Milan Cathedral, the historical city centre).

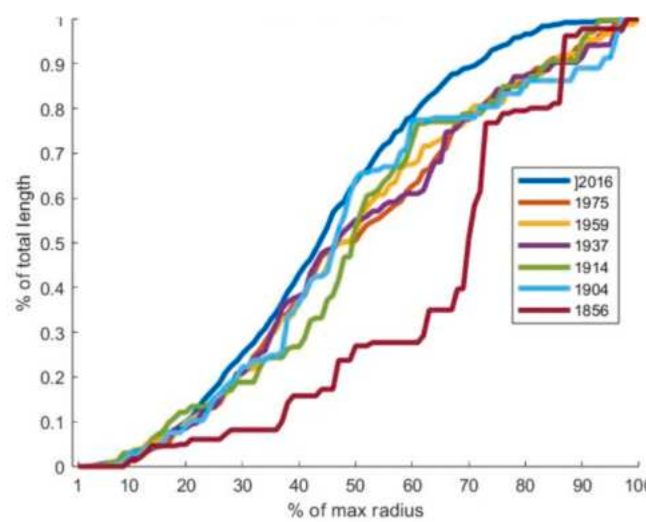

Fig. 3. Cumulative normalized sum of edge length for circular areas around the barycentres by increasing radii.

Table 2
Characteristics of the graphs considered in the study.

year	Nodes (N)	Edges (E)	Ratio (E/N)	Ratio (Surf/N) [m^2]	Ratio (Surf/E) [m^2]	Terminals	Average Degree	Diameter in nodes (NN)	Ratio (N/NN)	Diameter [m]
1856	39	54	1.3846	248,718	179,630	9	2.8	9	4.33	5364
1904	59	86	1.4576	164,407	112,791	16	2.9	10	5.90	9493
1914	87	129	1.4628	111,494	75,194	22	3.0	13	6.69	7444
1937	144	209	1.4514	67,361	46,411	38	2.9	17	8.47	12,805
1959	185	294	1.5892	52,432	32,993	43	3.2	18	10.27	15,187
1975	271	427	1.5756	35,793	22,717	54	3.2	24	11.29	16,628
2016	797	1269	1.5859	12,171	7644	98	3.2	43	18.53	9834

Legend: Surf. is the city surface in Section 2.1.

traffic volume, connectivity to important facilities, and number of origins and destinations crossing the link.

Complex network theory provides a different point of view (e.g., small world and scale free models) from which to explore properties of transportation networks. Latora and Marchini (2002) studied in detail the Boston underground network and proved that it has the "small world" property. Later, in (Derrible and Kennedy, 2010), the authors proved that metro networks are quite often both "scale-free" and "small world". Consequently, they also made suggestions on how to improve robustness of such networks.

Scott et al. (2006) proposed a method based on a network robustness index to evaluate the performance of a transportation network. Wu et al. (2018) introduced a novel centrality index, the node occupying probability, used to evaluate the robustness of metro networks. Jiang and Claramunt. (2016) calculated network connectedness, average path length, and clustering coefficient to investigate city street networks. Newman. (2001) proposed to calculate the average distance between each pair of nodes or the average path length as another technique to define the spread of a random network. Barthelemy (2004) applied betweenness centrality in large complex networks discovering that the nodes with a high betweenness would impose critical constraints on network security in real transportation systems.

Each of the indices mentioned above will provide us with a variety of information about the topology of the network or other desirable aspects depending on the considered weights. Moreover, those indices enable us to rank the nodes of a network. However, the obtained results from these indices reflect the node importance according to the principles underpinning the index design. Mending the aforementioned limits, we proposed new indices (Mussone et al., 2020; 2022), one of which is Icentr used in this research. It has been already applied in previous researches, exhibiting notable advantages and increasing our capability for a more extensive investigation of transportation networks.

The centrality index Icentr

The centrality index Icentr is extensively described in a previous study (Mussone et al., 2022), therefore, here we only mention its key features. It was created to evaluate the performance of transportation networks, taking into account both node weights and edge weights at the same time. Though not used in this study, it is worth noting that no other centrality index takes into account also the node weights.

Icentr calculates the score of each node by adding up the contributions of all edges in the graph, weighting them with a decrementing way in accordance with the order in which they are successively and continuously visited beginning at the node under consideration.

Consider an undirected simple graph $G = (V, E)$ that represents the network we take into consideration, and we assume that both nodes and edges are weighted. The nodes are $1, 2, \cdots, n$, and the edges are $e_1, e_2, \cdots, e_r$. Given an edge, each node in it is a neighbour of the other one. The notion of neighbour is at the core of the definition of Icentr. The weights of the nodes are $x_1, x_2, \cdots, x_n$ whereas the ones of the edges are $w_1, w_2, \cdots, w_r$, respectively. Let i_0 be the starting node. Firstly, we divide nodes and edges into levels. i_0 is the only level 0 node. Moreover, a node is in level h if it is neighbour of a level $h-1$ node and is not a neighbour of a node in level k for some $k < h-1$. Hence, the level 1 nodes are the neighbours of i_0. Of course, no node belongs to two different levels and because the graph G is connected, every node belongs to a level. To divide edges in levels, we remark that an edge $e = \{i, j\}$ connects two nodes either in different levels, or in the same level.

If e connects two nodes at different levels, let $x(e)$ be the weight of the node at the maximum level in e. Then, the contribution of e to the value Icentr takes at i_0 is

$$ic(e) = \frac{x(e)}{c^{lev(e)-1}} w(e) \quad (1)$$

where c is a number greater than 1. The higher this number, the lower the contribution of far levels.

If $e = \{i, j\}$ connects two nodes at the same level whose weights are x_i, x_j, respectively, the contribution of e to the value Icentr takes at i_0 is then

$$ic(e) = \frac{x_i + x_j}{2^* c^{lev(e)-1}} w(e) \quad (2)$$

The final value of the index is simply the sum of the partial contributions

$$Icentr(i_0) = \sum_{j=1}^{r} ic(e_j) \quad (3)$$

This choice of levels for the edges corresponds to the order in which they can appear in a path starting from i_0. Furthermore, in this research, we set c = 2.

If we assume that every node and every edge have weight 1, a node has a higher ranking if the number of edges closer to the node at the same level is higher. The partition of nodes into levels looks similar to that needed to construct a spanning tree, rooted at i_0.

The outcomes can be reported numerically in a text file or by using the graph (see, for example, Fig. 5) where the circles representing nodes have different colours and sizes, according to their index value.

Methodology and outcomes

Methodology

In this subsection we describe how the maps are worked out in order to make it possible their superposition (at least of the main spots) and the types of calculation made on graphs.

Geo-localization of maps

Geo-referencing the main points of each map to be able to superimpose maps and hence the graphs is one of the main developed tasks. In fact, the aim of georeferencing the maps is to enable the location of notable points within the city of Milan and to facilitate the correlation of changes in the transportation network with the city's expansion over time. Initially, the original maps from the twenty-first century are located and digitized into a vectorial system. Subsequently, these maps are overlaid onto the most recent municipal technical map to ensure consistency in spatial referencing.

To achieve this result, the maps are scaled and rotated based on three main points, recognizable starting from 1904: Porta Romana, Piazza Firenze, and Piazzale Loreto. In cases where these points were not identifiable, such as in the maps from 1856 or 1914, other notable positions, such as Piazzale Baiamonti and Porta Venezia, are used (Fig. 4).

Similarly, the same procedure is applied to the distorted graph maps. This time, the maps are scaled only along the Y-axis, using the same referencing points but only employing two of them for the graph distortion and the third one for verification. Once the scaling and referencing process is completed for all maps, the transportation network graphs are superimposed onto the corresponding historical maps. Care is taken to ensure alignment and referencing throughout the process to maintain the integrity and meaning of the analysis.

Calculation of centrality index Icentr values and their representation

For each graph, Icentr values are calculated for every node, taking into account two configurations: (see Fig. 5).

1. edge and node weights are set equal to 1, called the 'topological' case;
2. efge weights are equal to the reciprocal of distance between nodes, whilst node weights are ser to 1, called the 'weighted on distance' case.

In the second case, the application of distance's reciprocal penalizes

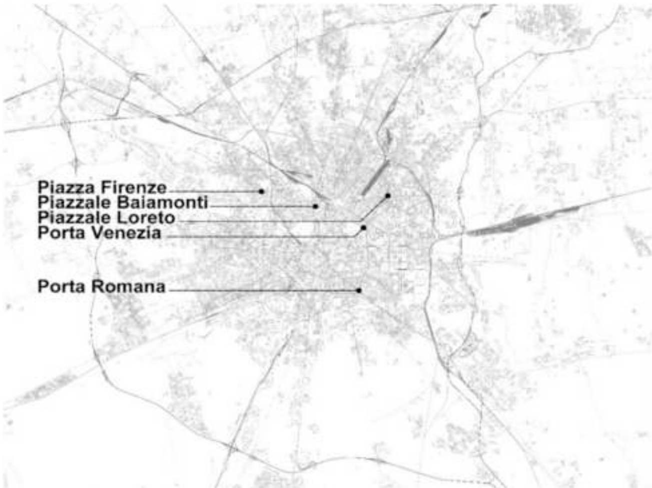

Fig. 4. Localizations of points used for the georeferencing and superimposition of graphs.

connections with a long edge since it takes into account the fact that increasing distance has a negative effect (in terms of transportation costs).

Icentr values are then normalized (in the min–max range) and subdivided into quintiles each of which is associated with a color, according to the following list:

1. [0.0, 0.2] cyan.
2.]0.2, 0.4] green.
3.]0.4, 0.6] yellow.
4.]0.6, 0.8] red.
5.]0.8, 1.0] black.

Actually, but only in the maps in Fig. 5, the values just equal to 1.0 are drawn in blue.

For each year and the two cases (topological and weight on distance), the barycenter of the nodes belonging to the fifth quantile (]0.8–1]) is calculated as the values of one standard deviation along x and y coordinates. The barycenter assumes the role of a pole in the underlying graph. To investigate the presence of possible further poles, a cluster analysis is carried out, which is significant for the topological 2016 case.

Outcomes

Fig. 5 (from 5.1 to 5.7) show the Icenter values on the graphs subdivided into quintiles. The left (a) series reports the topological case, whereas the right (b) series reports the weight on distance case.

The number of nodes in each quintile and their percentage of the total number of nodes per year for the two weight instances are shown in Tables 3 and 4. To better visualize outcomes, pie charts displaying them are also shown in Figs. 6 and 7.

Fig. 8 show the locations of the nodes with the highest Icentr values for the topological (8a) and weighted on distance (8b) cases, respectively, for each year. The underlying map is that of the year 2016 to include all possible locations, but this implies that some locations might not be exactly located in a node of the 2016 graph.

Fig. 9 show, for each graph, the locations of the barycentre of nodes with Icentr values only in the fifth quintile for the topological (9a) and the weighted on distance (9b) cases, respectively. The barycentre is calculated by averaging the coordinates of the nodes. The ellipses drawn around these barycentre points have axes equal to one standard deviation of the same data. In Fig. 10, the top 80 % index values for all years are drawn. This synoptic representation allows for an immediate view of how much the most relevant points moved on the city over the years. Fig. 11 presents a perspective-wise view of the same data in order to enhance the visualization of these results.

Fig. 12 reports the cluster analysis carried out by using the k-means algorithm and the silhouette criterion for the year 2016 and for the topological case using only the last quintile data (in the ramge]0.8,1]). Actually, in the other years and cases, the clustering produces clusters with centroid locations so close to each other that the outcomes could not be deemed significant.

Discussion

Although the maps were selected primarily based on what was truly usable, the resulting graphs exhibit a reasonably consistent rise in the number of nodes and other graph attributes, giving us sufficient confidence in their representativeness.

With two exceptions—the average degree of graph nodes and the graph diameter in meters—all other characteristics show an upward trend between 1914 and 2016. Over those years, some new edges are introduced in the internal regions of the network, making the shortest routes shorter than previously. This is likely to occur at the expense of an extension of the network beyond the periphery.

It is important to note that when assessing Icentr results, we take into account normalised values for comparison's purposes, meaning that the network's size is irrelevant in these analyses.

When analysing Icentr outcomes on the maps (figures from 5.1 to 5.7), the first conclusion is that there is generally a difference between the topological case (all weights are equal to 1) and the weights-on-distance case (weights are the reciprocal of the distance between nodes). The general trend is that, apart from some changes in the central area of the maps, the quintile of nodes decreases progressively from the centre to the periphery. This means that the more peripheral the node, the longer the connecting edge, and the lower the Icentr value. Then the difference between topological and weighted cases can be explained by the longer length that edges have, particularly in peripheral areas. Tables 3 and 4 and Figs. 6 and 7 give more insights in this regard. Generally, in the first and second quintiles (the intervals [0.0–0.2] and [0.2–0.4], respectively), the percentage of data increases in the weighted-on-distance case.

The 1904, 1914, 1959, and 1975 years exhibit similar percentages among them and the other years, though they are slightly different from topological and weighted-on-distance cases. What is different in the two cases and from the other years are the 1856 and 1937 years, and partially the 2016 year. The 1856 year also exhibits the highest percentage for the fifth quintile, followed by the 1937 year, but only for the topological case. This is due to the number of nodes denser in the central area, to the overall small area, and, consequently, to the short distance between nodes. Anyway, the first four quintiles are more or less simultaneously present, with percentages around 20 %. If the network develops more in the radial directions than in circular ones, the peripheral nodes will get fewer contributions, and their Icentr values will belong to the lower quintiles.

It can be of interest to combine the previous analysis with the data on population, which represents a determinant variable in constituting transportation demand.

The first data on Milan's population inside the range into analysis refers to 1861, when the city, which consisted only of the inner core of the present city and is now regarded as the city centre, had a population of 267,618 units. Due to the favourable economic situation, the city grew in subsequent years. The population increased, and the town extended its borders by incorporating the so-called Corpi Santi municipalities in 1873. This growth is evidenced by the number of people living in Milan at the second historical moment chosen for the analysis, 1904. The population in 1901 was 538,478 units. As mentioned, Milan experienced overwhelming growth during this period, followed by some attempts to control the expansion with a quick succession of urban plans. The following evolution of the analysis considered the situation of

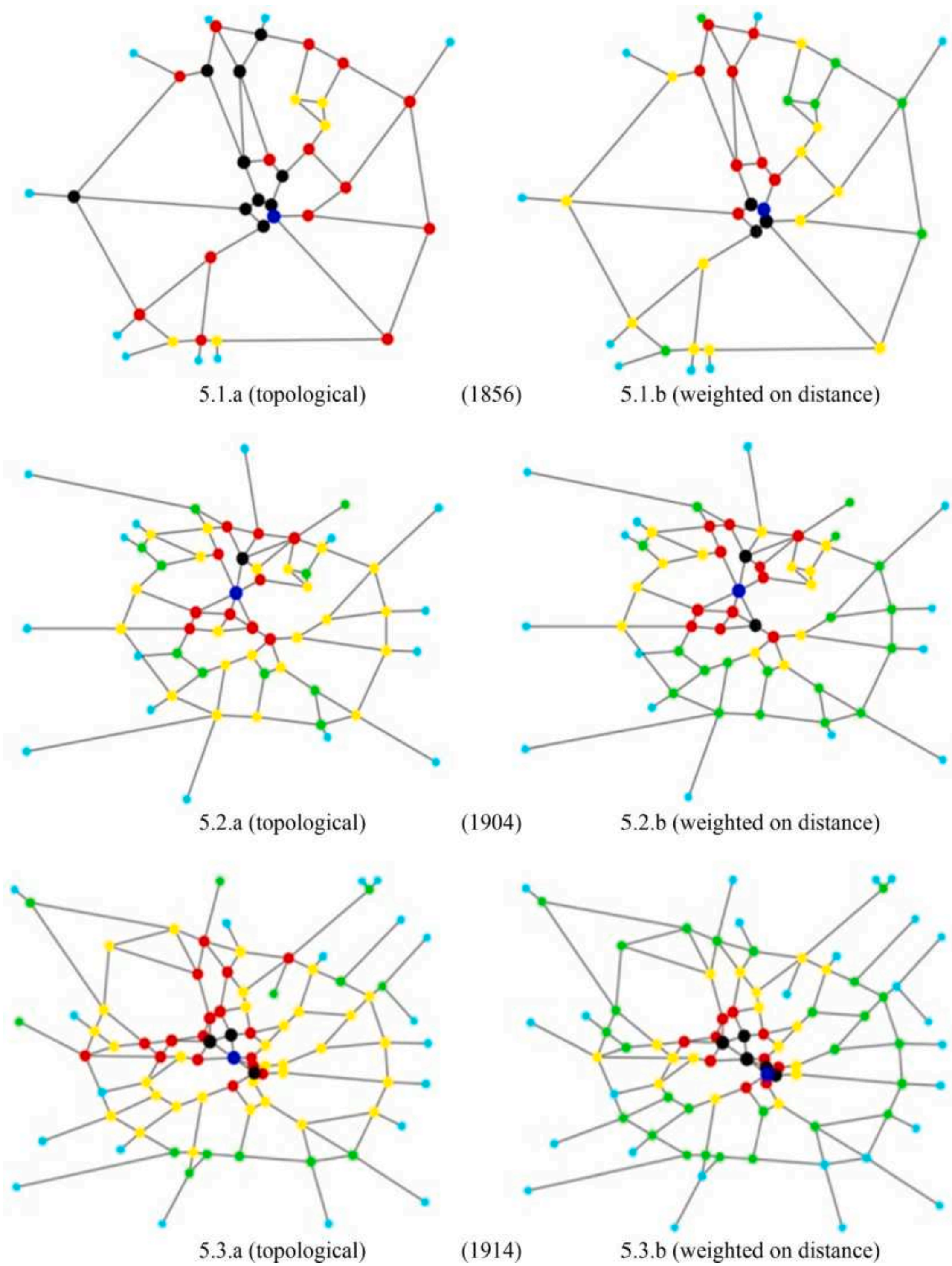

Fig. 5. Distributions of normalized Icentrr values by year, weight ((a) topological and (b) weighted on distance), and quintiles. (Legend: cyan = [0.0,0.2], green =]0.2–0.4], yellow =]0.4–0.6], red =]0.6–0.8], black =]0.8–1.0], blue = top value). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the lines in 1914. The closest data regarding population refers to 1911, with a population of 701,401, and reflects one of the moments with the highest expansion rates, with a 30 % increase in 10 years. Following 1914, the First World War affected the city's development and halted it during the conflict. In 1937, the population rose again thanks to post-war reconstruction and investments that boosted recovery. In 1926, the tram network was reformed, significantly reorganising the lines around the Milan Cathedral (Duomo), and due to the rapid growth of the city, bus lines were also introduced. Around the same time, another enlargement of the municipality was executed. In the statistics of 1936, the population increased again, crossing the target of one million inhabitants and reaching 1,115,768 units. Shortly after, another world war impacted the city's growth and development. The year 1959, in some ways, reflects this period of slow expansion of the urbanised areas,

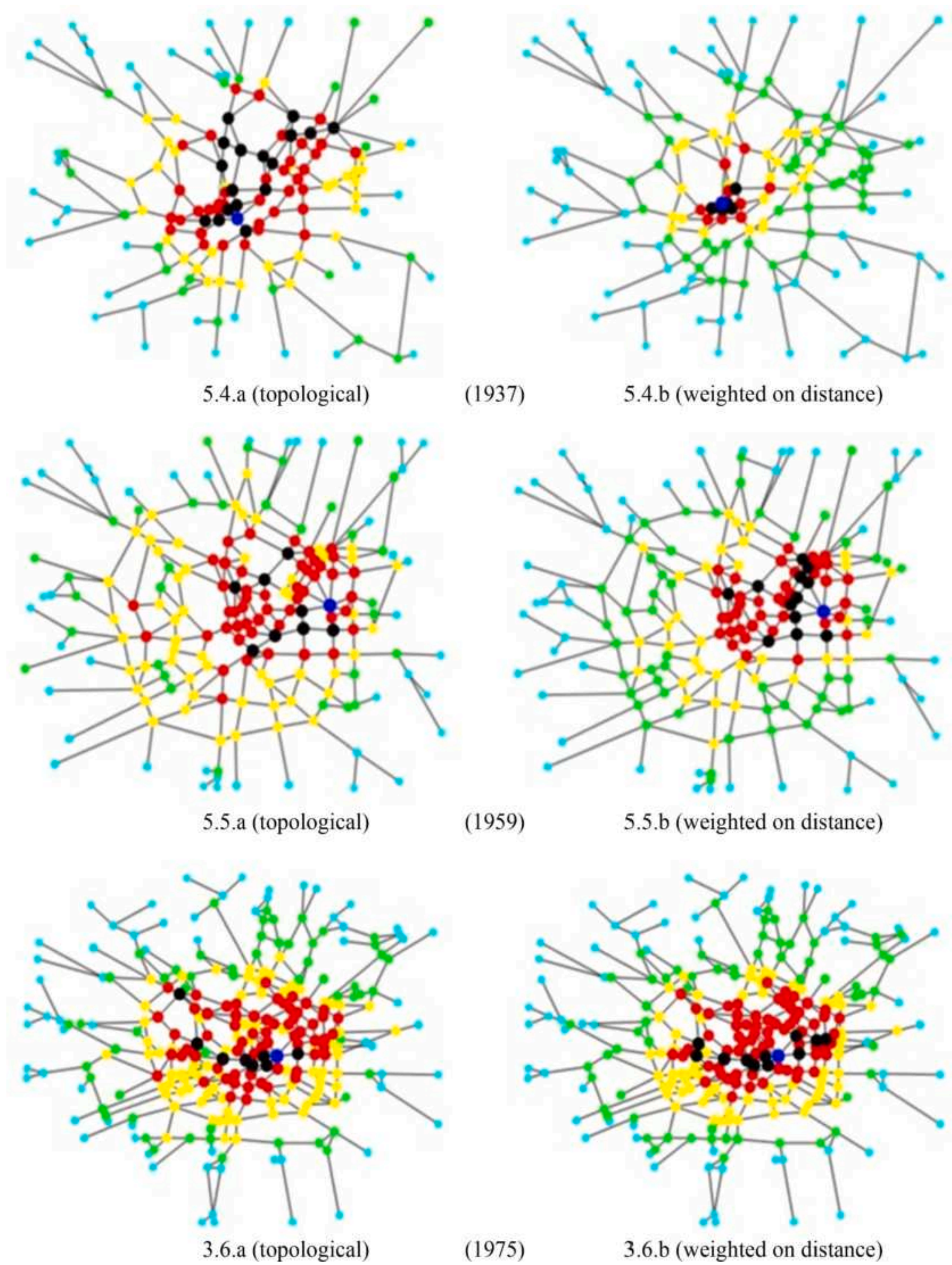

Fig. 5. (*continued*).

which contrasts with the expansion and densification of the transit network, reducing the gap between the expansion of the city and the consequent expansion of the network. A few years later, in 1961, the population of Milan was set at 1,582,421 units, showcasing the relentless growth of a bustling city. The years 1975 and 2016 are quite distant in time from each other: Although still in 1971 the population of Milan was increasing, reaching its peak at 1,732,000 million inhabitants, shortly after, in 1981, the population declined and continued declining up to the 2000′ss, when the trend was reversed, arriving in 2016 when the population was 1,351,562 units. Analysis of topological Icentr by year shows different trends between two groups of years: namely, 1856, 1904, 1914, and 1937, 1958, 1975, 2016. In the first group, the first quintile percentages increase whereas the top quintile percentages decrease from 1856 to 1914; in the second group, more or less the opposite occurs, though in both groups the percentages for the top quintile are very low (except for years 1856 and 1937, as already underlined). For the weighted case, the same two groups can be identified, and when in one the percentages increase, in the other they decrease. This stresses again the differences in the structural shape of the transportation networks, mainly radial in the first group and

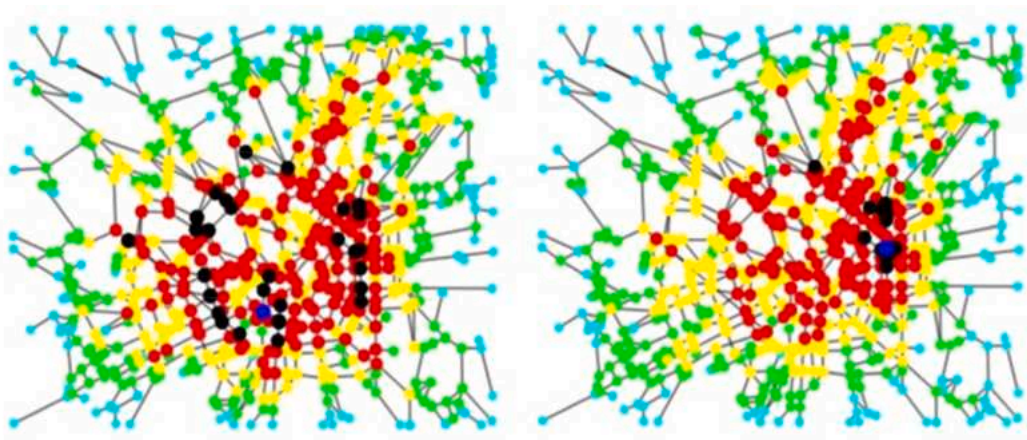

Fig. 5. (*continued*).

Table 3
Number of nodes by quintiles for topological Icentr Centrality index.

Year	[0.0–0.2]	]0.2–0.4]	]0.4–0.6]	]0.6–0.8]	]0.8–1.0]
1856	9(23 %)	0(0 %)	5(13 %)	14(36 %)	11(28 %)
1904	15(26 %)	10(17 %)	22(37 %)	10(17 %)	2(3 %)
1914	19(22 %)	13(15 %)	34(39 %)	17(20 %)	4(4 %)
1937	37(26 %)	21(15 %)	31(21 %)	37(26 %)	18(12 %)
1959	42(23 %)	32(17 %)	54(29 %)	48(26 %)	9(5 %)
1975	65(24 %)	56(21 %)	79(29 %)	62(23 %)	9(3 %)
2016	136(17 %)	211(26 %)	240(30 %)	181(23 %)	29(4 %)

Table 4
Number of nodes by quintiles for weighted on distance Icentr Centrality index.

Year	[0.0–0.2]	]0.2–0.4]	]0.4–0.6]	]0.6–0.8]	]0.8–1.0]
1856	8(21 %)	7(18 %)	12(30 %)	8(21 %)	4(10 %)
1904	14(24 %)	18(31 %)	13(22 %)	11(18 %)	3(5 %)
1914	26(30 %)	28(32 %)	17(20 %)	10(11 %)	6(7 %)
1937	58(40 %)	47(33 %)	24(17 %)	9(6 %)	6(4 %)
1959	48(26 %)	52(28 %)	34(18 %)	38(21 %)	13(7 %)
1975	66(24 %)	62(23 %)	66(24 %)	65(24 %)	12(5 %)
2016	141(18 %)	231(29 %)	255(32 %)	156(19 %)	14(2 %)

increasingly circular in the second one.

Fig. 8 shows the locations of the node with the highest score by year for the topological and weighted cases. These points are a little bit more scattered far from the central part of the graph for the topological case than the weighted on distance one. Actually, the locations are all different per year, and it does not seem to recognize any time sequence for their differences. The distinction between the topological and weighted examples for the year 2016—the former is located far southwest of the centre, while the latter is located far northeast—is especially noteworthy. As a result, compared to the southeast, the north-eastern portion of the network is now denser (has shorter edges). A more thorough study has been conducted on this, as shown in Section 4, as it is unlikely that these points are likewise also the barycentre of the final quintile nodes.

Fig. 9 shows the locations of the barycentre of node coordinates for each year separately, together with the ellipse delimiting the one standard deviation from the barycentre itself. As expected, the axes are (a bit) longer for the topological case (Fig. 9a), especially for the 2016 year and then for the 1856 year. The locations of the barycentre are quite close to the highest score points, and this is also partially expected by considering Icentr definition and the radial shape of the graphs. Of course, the presence of multiple poles could modify this relationship.

This aspect is investigated for the 2016 year (topological case), just

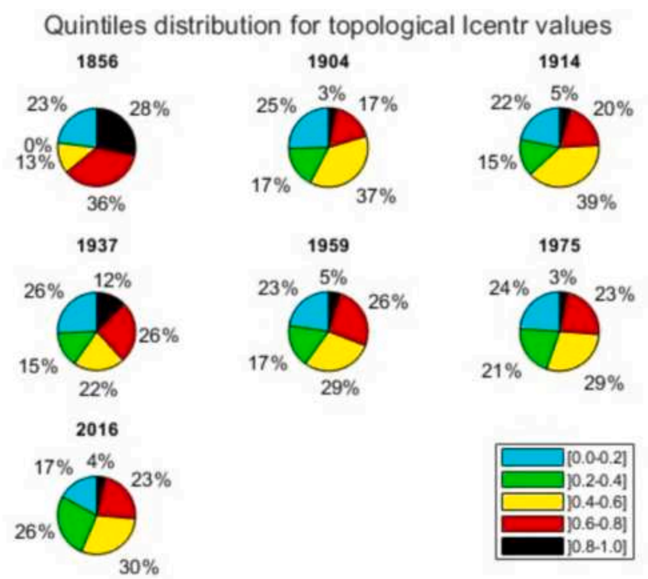

Fig. 6. Pie charts of number of nodes for Icentr topological values by quintiles and by year.

because of the larger ellipse. It is found that, actually, three clusters of the fifth quintile nodes can be identified, as reported in Fig. 12. The three clusters are located mainly on one of the main rings of the city, forming a triangle with vertices on the east, north-west, and south-west sides. This can be considered a first clue to the expansion and the increase in complexity of the graph (and hence of the city) towards the suburbs. From a technical point of view, this can occur because Icentr weights higher levels (that is, farer nodes) progressively less.

Fig. 11 presents a synoptic view of the top 80 % Icentr values by year for both the topological and weighted cases. This allows for a direct comparison of the highest values for each year, highlighting the changes in their position and distribution over time. (Fig. 11a and 11b, respectively).

Lastly, we go over the method's limitations, the findings of this study, and potential uses in transportation planning.

One significant barrier to conducting the historical analysis may be the gathering of information for the graphs and all variables characterising the various elements influencing urbanistic change, starting with the transportation one. Not to mention, networks are getting bigger and bigger, which raises computational issues.

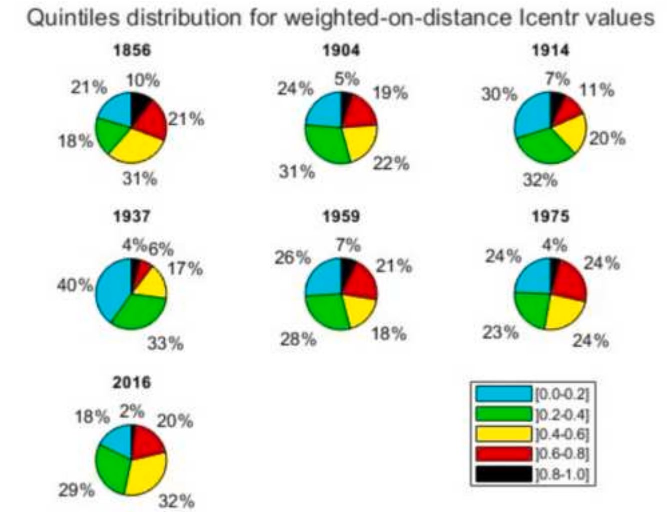

Fig. 7. Pie charts of number of nodes for Icentr weighted on distance values by quintiles and by year.

One further drawback of employing centrality indices is that, while they are useful for collecting pictures at specific times, they are inherently static. An appropriate series of discrete events can be used to build out a dynamic analysis.

One of the analysis's limitations is the absence of demand data, which in fact might aid in a deeper understanding of how it interacts with supply and in examining how the centrality indices vary depending on the quality of service provided. Furthermore, examining the relationship between daily ridership or peak hour demand and centrality indices could be intriguing.

Conclusions

The paper presents an analysis of historical maps of surface transport networks in Milan from 1856 to 2016. Among the analyses that may be done to comprehend the whole process of urbanisation, this one can be regarded as basic. The fundamental idea is that the transport network's evolution is severely limited by its past configuration because it is a complex system.

The analysis has concentrated on the topological characteristics of the networks by using tools of graph theory. In particular, a novel centrality index has been used, Icentr, as presented in an earlier study (Mussone et al., 2022), capable of capturing and synthesizing the main features of a graph. The objective of the analysis is threefold: checking the application of Icentr, comparing graphs, and describing the evolution of the city transportation network.

The first objective is achieved by geolocating maps and graphs and superimposing them onto their respective plans. This process effectively illustrates the evolution and variations in the positioning of the analyzed main values.

Icentr is governed by fairly straightforward rules;

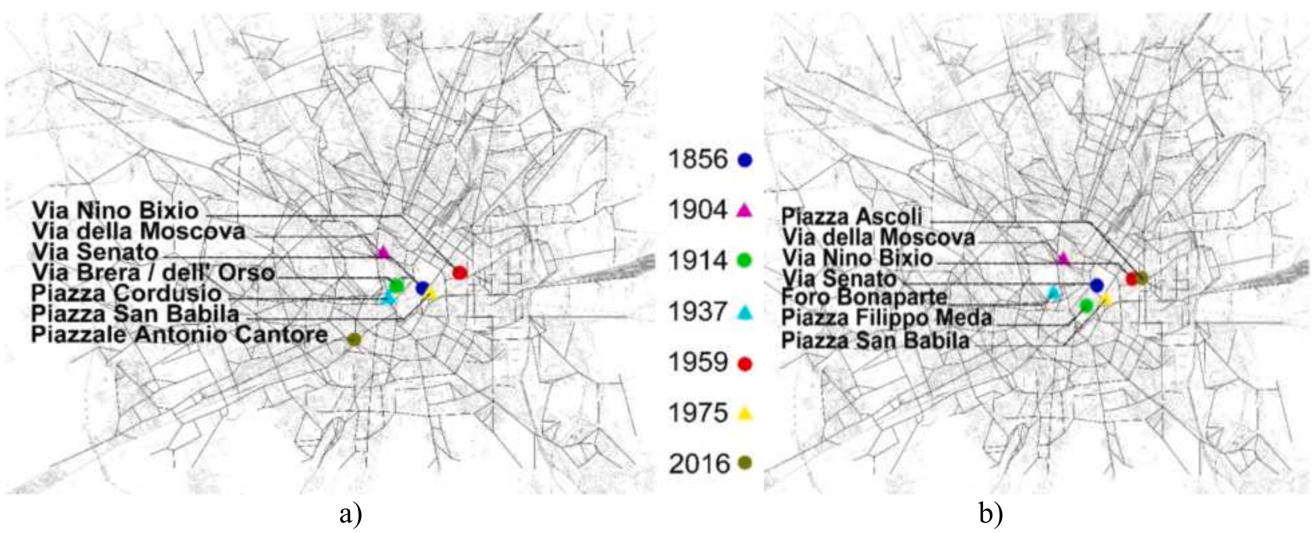

Fig. 8. Localization of the highest Icentr value by year: a) topological, b) weighted on distance.

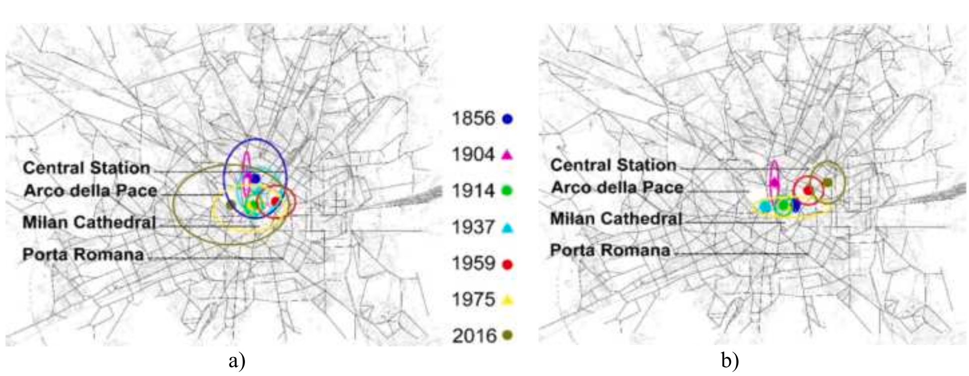

Fig. 9. Localization of the barycentre of the highest 80 % Icentr values by years: a) topological values, b) weighted on distance values; ellipses have axes equal to one standard deviation both on x and y coordinates (labels point to the closest most known places).

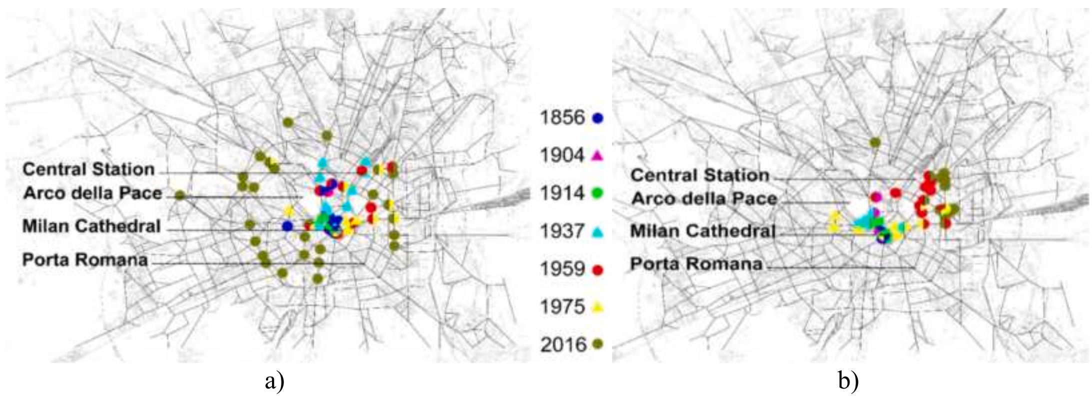

Fig. 10. Top 80% (5th quintile) Icentr values for all years, a) topological, b) weighted on distance case (labels point to the closest most known places)..

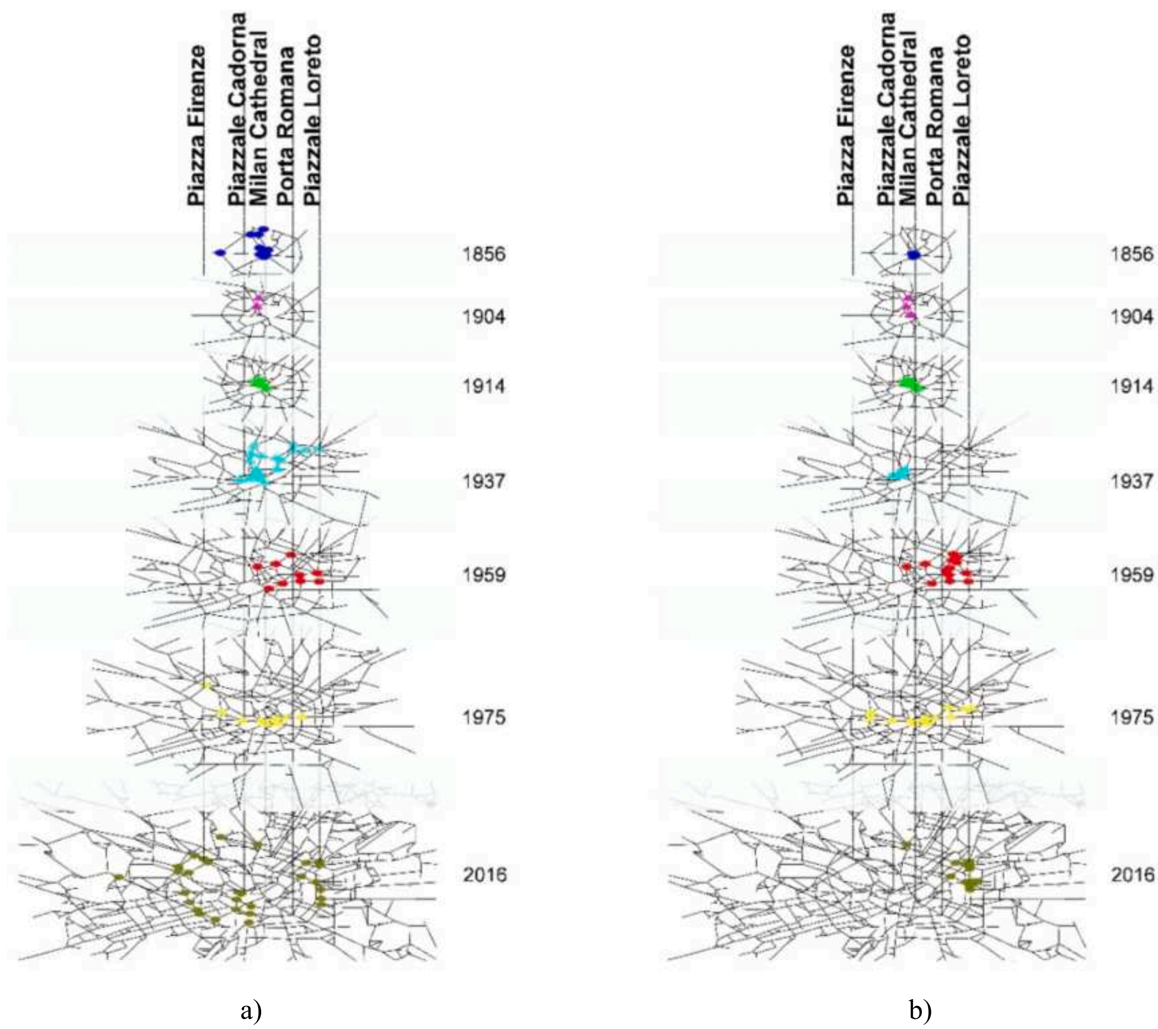

Fig. 11. Prospective synoptic view of all seven top 80% Icentr outcomes: a) topological, b) weighted on distance values.

- increasing the number of edges improves the (absolute value of the) index mostly locally;
- the (absolute value of the) index increases with the degree of the added nodes, primarily locally.

Regarding the latter, Icentr has provided accurate information regarding the evolution of Milan's surface transport system over the course of more than a century.

Milan's evolution followed a different path, first expanding outward and then tightening its ties in a cyclical fashion. The sequence of maps (Fig. 1) of the years 1856, 1904, and 1914, as well as 1937, 1959, and 1975, can be compared to determine this transition. A combination of both marked the shift from 1975 to 2016. For the topological scenario, the years 1856 and 1937, which initiated such sequences, have the highest proportion of nodes in the fifth quintile (Table 3). The decreased edge/node ratio (Table 2) for the years 1856 and 1937 supports this;

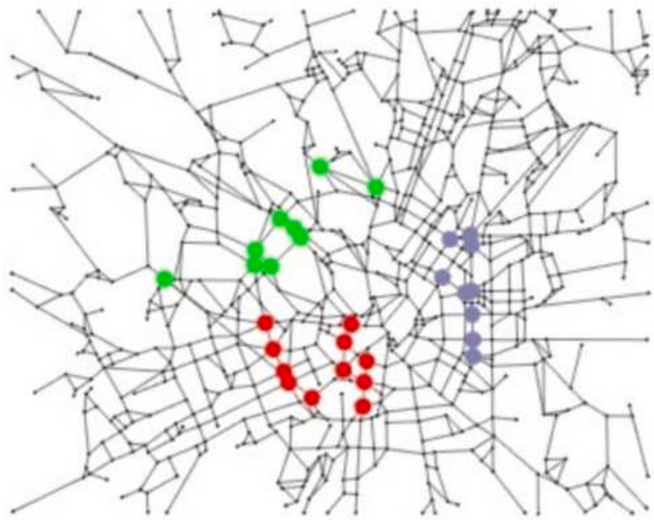

Fig. 12. Clusters of top 80% (5th quintile) Icentr topological values for year 2016 (see also Figure 5.7.a).

also, a notable decrease in diameter and an increase in average degree are seen in 1937.

We can also detect the presence of poles different from the barycentre using the suggested method. Actually, at least three major poles may be distinguished on the map as it stands as of 2016 (Fig. 11).

Numerous topics that this paper is unable to touch on can be covered in future works.

The research will then go in two directions:

- it will examine further case studies and.
- it makes recommendations on how to best develop a transport network.

The term "best" here refers to both determining the lowest overall cost for travellers as well as favouring future expansions without impeding them.

Although the method is intended for all scholars, transportation engineers and city planners will find it most useful. The methods that have been suggested are mostly descriptive, but they can also be utilised in a "what if" fashion to examine or evaluate whether the intended scenarios' transport network performance better meets objectives and requirements. Utilising more centrality indices and contrasting them with Icentr may help us better understand the network's evolution. The consideration of several factors associated with a transportation network, such as constructing settlements, householders or occupants, and employment, can be achieved by utilising weights or vectors of (normalised) weights.

One of the research's ultimate goals is to examine the connection between graph features and transport demand (due to the specific urbanisation of the city under investigation). Under this perspective, the inclusion in the analysis of underground railway transport systems would become fundamental.

Finally, we can draw the conclusion that the methodology presented has been successfully used, and all the outcomes suggest that it can also be applied to other cities.

CRediT authorship contribution statement

Lorenzo Mussone: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Elia Villa Aliberti:** Writing – review & editing, Writing – original draft, Visualization, Data curation. **Roberto Notari:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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