Analysis of the Road Network Evolution through Geographical Information Extracted from Historical Maps: A Case Study of Manila, Philippines

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Abstract—**We present a comparison of the network structure of the road network of Manila, the historical capital of the Philippines, for the years 1908 and 2018. The 1908 data is extracted from a historical map that is georeferenced, redrawn for the street network, and saved as a digital Geographical Information Systems (GIS) data. On the other hand, the 2018 map is imported from OpenStreetMap (OSM). The roads are exported as connected nodes, which are then analyzed for their network properties using the tools from complex network analysis. Degree centrality measures show no discernible patterns for both the old and new maps, suggesting that the majority of the road networks have predominantly grid-like patterns. The development of the road network is more discernible from the changes in the closeness and betweenness centrality measures, which have shown a general outward movement from the geographical center of the city. Both the map digitization technique and the network centrality analyses can be extended to incorporate a wider set of cities and longer time periods, providing a straightforward quantitative description of the urban road network growth.**

Index Terms—**road network, historical maps, georeferencing, map digitization, network centrality measures, Manila**

I. Introduction

Urbanization, which is at its fastest globally over the last few decades [1], leaves behind measureable spatial records in the form of static physical elements such as road networks [2], [3], infrastructure [4], and buildings [5], among others. Among these spatial features, the road networks are the ones that trace their histories from even older generations, way before the aforementioned urban boom [6]. Understanding the historical evolution of the road is a timely and urgent concern because road structure affects the global efficiency of the network in transporting the goods and services across the urban zone [7]-[11]. This, in turn, is of great consequence to the quality of life and the well-being of the general population living in these metropolitan areas [12], [13].

The road network evolution can be gleaned qualitatively from timelapse satellite photographs collected over the last few decades. However, the availability of satellite images spans only a few decades back [14], limiting the capability to explore for even older periods. More importantly, a photographic record only provides a coarse-grained visual description of the city evolution. A more complete and reliable description of the city road growth must be based on quantitative metrics.

In this work, we simultaneously address these issues and present quantitative description of the road network evolution of a representative urban space. We address the temporal limitation by utilizing historical maps. The hand-drawn maps, although containing geographical inaccuracies in their raw form, provide a complete information about the network structure, i.e. which roads lead to where, etc. Moreover, with the advent of rapid GIS computational tools, we have been able to address these errors and made the maps correspond to real-world coordinates. Upon extracting the structure and geography, we are able to describe the evolution of the road network in quantitative terms using the tools of complex network theory. While the method can be applied to any road networks from historical maps, here, we show the efficacy of the method for the particular case of Manila, the capital of the Philippines. We show that the self-organization of the road network of Manila has given rise to emergent unexpected properties.

II. Data and Methods

A. Historical and Contemporary Map Data

To enable us to analyze large volumes of data using complex network techniques, it is crucial to be able to obtain substantially complete and accurate geographical information from historical and contemporary sources. Historical maps predate the digital maps obtained from satellite images, and are thus useful for extending the temporal scope of the study. Needless to say, a historical map, while correctly depicting the structure of the road network during the period when it was created, lacks the geographical accuracy required for quantitative analyses.

Manuscript received April 1, 2019; revised July 25, 2019.

doi: 10.12720/jait.10.3.114-118

As such, a historical map should first be subjected to proper georeferencing before digitization and data extraction.

In this work, we use a historical map of the city of Manila in the year 1908. The historical maps are obtained by digitally scanning an actual physical copy of the map obtained from the Filipinas Heritage Library using the Niji scanner with a resolution of 300 dpi. We georeferenced the historical map with respect to the OSM using the OpenLayer Plug-in in QGIS. We do this by matching corresponding Ground Control Points (GCP) in both historical and OSM map. Using the WGS 84 Pseudo Mercator as the reference coordinate system and using the thin plate spline transformation and nearest-neighbour resampling method, we obtained a mean error of 8.47×10^{-7}.

Using the georeferences historical map, a shapefile of the 1908 Manila road network is drawn in QGIS. The roads are traced by following the hand-drawn roads from the map. While a combination of several techniques from image processing and machine learning can be used to make this process automated, we opted to manually trace the roads in QGIS to ensure substantial accuracy, especially in regions where the roads are no longer extant. We have extracted 627 roads from the 1908 Manila map. This road network shapefile is then extracted for the nodes, which are geographical points of references such as intersections and bends. Using the built-in function for node extraction in QGIS, the 1908 Manila shapefile has yielded 4727 nodes. All the geographical data are reported as a sequence of values (r, ϕ, θ), where r is the road where the node belongs to, ϕ is the latitude, and θ is the longitude.

The contemporary map is extracted from the OpenStreetMap (OSM) imported through QGIS. The OSM data is accurate as of January 2018, and contains 20,470 nodes from the 4,150 individually-named roads and bridges. For the purpose of this study, the 2018 map is used as baseline references when assessing the accuracy of the geographical locations generated from the historical map.

B. Complex Network Analysis: Centrality Measures

The road network formation has been viewed as a complex self-organizing process [15]-[17]. Because of its structure, the road networks can also be understood using the techniques developed in complex network theory [18]. For our purpose, we track the centrality measures of the nodes in the street networks of the 1908 and 2018 data.

Mathematically, graphs are constructs made up of *agents* or *nodes* whose interactions are modeled by a *connection* or *edge* drawn between them. For this work, we can think of an individual road to be a path in the network where a geographical node i is connected to it neighbor nodes by edges that represent the physical portions of the road. The degree k_i of the node i refers to the number of neighbors connected to it. In traversing the network, the minimum number of nodes required to reach a j from i is called the shortest path length ℓ_{ij}.

The influence of a node i can therefore be measured using measures of its centrality relative to the other nodes. The degree centrality $d_i = k_i/k_{\max}$, where $k_{\max}$ is the maximum degree among all the nodes in the network, measures how many neighbors a node has relative to the entire network. The closeness centrality, on the other hand, is given by $g_i = [\sum\ell_{ij}]^{-1}$, for all $j\neq i$; this metric gives the structural center of the network, as the node with highest closeness centrality has the minimum shortest paths to all the other nodes. Finally, the betweenness centrality $b_i = \sum[\sigma_{hj}(i)/\sigma_{hj}]$, for all $h\neq j\neq i$, measures how many times the node i has appeared, $\sigma_{hj}(i)$, in the collection of all shortest paths in the network, σ_{hj}. For this metric, the influence of the node i is evident from the fact that the network will reroute and have more longer ℓ_{ij}'s if it is removed. The structural differences between the historical and contemporary maps can therefore be quantified using these metrics.

III. Results and Discussion

A. Comparisons and Remarks on Historical Map Accuracy

In Fig. 1(a), we present the 2018 road network structure of Manila overlaying the geographical conditions of the city. The city is physically separated into the northern and southern regions by the Pasig River that runs through the middle portion of the city. The river drains into the Manila Bay to the west. These geographical constraints have affected the structure of the road network throughout the evolution and development of the city.

In Fig. 1(b), we plot together the 1908 and 2018 road networks of Manila to observe the evolution of the road network. In over a century of development, the northern portions of Manila have become densely-filled with roads, in line with the corresponding growth of the suburbs of the capital. Interestingly, the northeastern part of the city, where the differences in the road network cover is most apparent, is adjacent to Quezon City, a city that was drawn from a master plan and served as the capital at one point. On the other hand, the northwestern sections of the city, where differences are also apparent, resulted from the recent efforts to reclaim the area facing the Manila Bay for the establishment of ports and other government and business establishments.

The dotted box in Fig. 1(b) is magnified in Fig. 1(c). This region is the Intramuros area, the oldest district in the city that was established as the seat of government since the late 1500s. Because this district has been well-preserved up to now, we chose this section of the city for analyzing the accuracy of the historical map digitization procedure used. In Fig. 1(c), the grid-like road network of Intramuros obtained from the 1908 map shows significant deviations from those obtained from the 2018 OSM data. We believe that the finite width of the streets from the hand-drawn map has contributed to the observed deviations. When georeferenced, these widths actually correspond to as wide as a 70 m width, which introduces large uncertainties, even for a careful manual tracing in QGIS. By comparing the intersection nodes at of Intramuros for the 1908 and 2018 data, we have computed a deviation of around ±43 m, which we can use as a baseline measure of accuracy for the procedure we used.

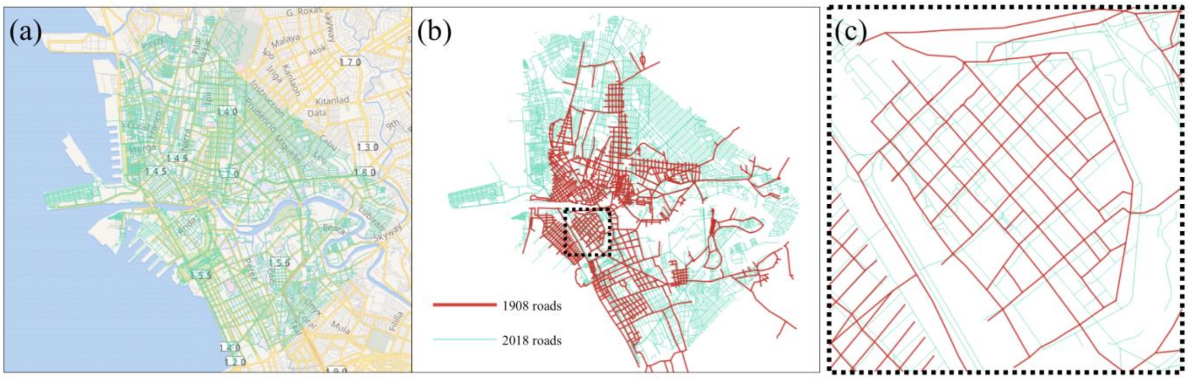

Figure 1. (a) The geographical location of the City of Manila, Philippines, showing the surrounding waters and the road network overlay. The base map is from Wikimedia Commons. (b) The historical (1908) and contemporary (2018) maps show large differences, visually showing the road network evolution in over a century of development. (c) Zooming in to the oldest part of the city, Intramuros, shows the differences in the geographical placements of the roads for the historical and contemporary map shapefiles.

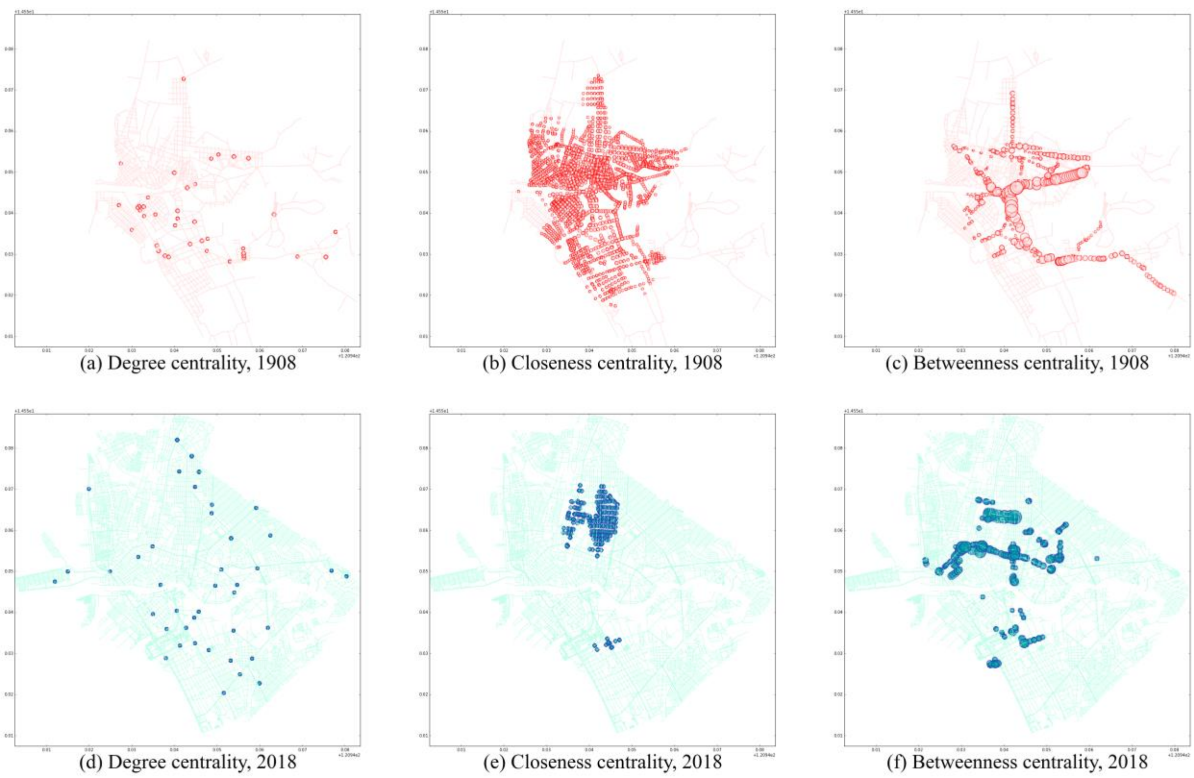

Figure 2. Centrality profiles for the (a)-(c) 1908 and (d)-(f) 2018 road networks. The highest degree centralities are observed for the non-grid locations; there is no discernible pattern for (a) 1908 and (d) 2018. The closeness centralities, on the other hand, show an effective fragmentation of the network: (b) in 1908, the most of the nodes have high closeness centrality values, while (e) in 2018, there is a concentration of high-closeness-centrality nodes for both the northern and southern regions. The betweenness centrality has also evolved, (c) from a pattern that is highly dependent on the bridges across the Pasig River in 1908 to (f) one where the most central nodes are within the northern and southern districts in 2018.

B. Changes in Network Centrality

We computed the centrality measures for all the nodes in the 1908 and 2018 data. In Fig. 2, we present the most central nodes, i.e. those with centrality values above the average. The node sizes show the relative centrality values. The top [bottom] row is for the 1908 [2018] data.

The profiles of the degree centrality d show no discernible pattern for both the 1908, Fig. 2(a), and 2018, Fig. 2(d), networks. An analysis of the data reveals that most of the nodes have degrees k = 4 (simple intersections) and k = 2 (nodes at the bends). The high d nodes that emerge in Fig. 2(a) and (d) are incidental occurrences of intersections having more than four outgoing directions. As such, we deem it to be poor indicator of the differences that have transpired over the network through the course of its development.

On the other hand, we observe a noticeable contrast in the profiles of the closeness centrality *g*. In the 1908 map, most of the nodes have a high closeness centrality value such that almost all of these nodes can be considered easy to reach regardless of your starting node or location. We therefore observe a clustering of highly central nodes at the geographical center of the city in Fig. 2(b). Over time, and with the addition of more roads, more intersection nodes are added to the system. Therefore, even if the physical distance among nodes have decreased, the closeness centrality values *g* decreased. In Fig. 2(e), the 2018 profile shows that the highly central nodes have moved away from the geographical center of the city due to the increase in the node densities at the peripheral locations. In fact, we observe fragmentation of the northern and southern sections of the city in the 2018 profile.

Finally, in Fig. 2(c) and 2(f) we also observed a significant difference in the profiles of betweenness centrality *b* of the two data sets. In 1908, shown in Fig. 2(c), there are fewer highly central nodes, but with significantly higher *b* values. In particular, the nodes with the highest *b* runs through the middle portion of the city where the bridges connecting the north and the south sides of Manila can be found. These nodes are well-utilized when traversing from the northern to the southern region and vice versa. On the other hand, in the 2018 map shown in Fig. 2(f), we observe that the high-*b* nodes can now be found away from the geographical center, indicating less dependence on the connecting bridges. This is a consequence of two interrelated mechanisms: (i) the city has developed the northeastern portion, as shown in the map comparisons in Fig. 1(b), moving the concentration of nodes away from the river; and (ii) the city has developed new ways of traversing from the northern to the southern parts of the city.

The implications of the observed changes in the profiles of the highly central nodes may further be explored when we compare our results with those of Barthelémy *et al.* [19] using historical data from Paris, France. In their work, they noted the effect of the drastic changes in the centrality profiles of the city due to the changes imposed during the Haussmann period in the late 1700s to early 1800s. The modifications in the road structure resulted in the evolution of the high-*b* node profiles from a centralized to a leaf-like venation pattern, which is deemed to have made the network more robust and efficient. In the Manila data, however, no such drastic changes in the road network profile has been implemented from a top-level plan; instead, the new network was allowed to grow organically in time. As such, we do not see a reticulated pattern about the center in Fig. 2(f).

Most of the central nodes in the northern section of the city are found along the stroke of major highway called the Recto Avenue and Mendiola. Incidentally, this stretch of road is an old commercial district, and will lead to the Malacañang Palace by the Pasig River. This suggests that to reach the other locations in Manila, people pass through the avenue first. Interestingly, we note that we can also observe many nodes of high betweeness centrality along this said stroke of road, then known as Azcarraga Road, in the 1908 map. In 2018, due to the mechanisms of road growth discussed earlier, the *b* values decreased. However, since this portion is still represented by high-*b* nodes, we can say that this is a historically important avenue.

IV. Conclusion

In this work, we have provided a comparison of the road network structure of Manila from two period separated by more than a hundred years. We have utilized a historical map of Manila to broaden the temporal scope of road network analysis. Real spatial coordinates have been incorporated into the ordinary 2D raster map via georeferencing. To turn it into useful form, we manually drew the network in QGIS by tracing the centerlines of the roads in the hand-drawn maps that vary in width. These widths incorporate errors in the digitization such that there is an offset between the old and current road network. We accounted for this offset by looking at the set of nodes in the extant region of the city, and found a deviation in the order of 10^1 m.

The method that we used for extracting digital road network information from a historical map is straightforward and within a reasonable degree of accuracy. While there are systematic errors that emerge due to the hand-drawn nature of the maps, the method may further be corrected using finer calibrations in the extant regions of the city. The process can also be automated using computational tools such as line detection through Hough transforms, or FFT filters, among others. The method is relatively easy to implement, and may be extended in both time (i.e. maps from other years) and space (i.e. sets of maps of other cities).

From the extracted road network and nodes, the mathematical graph is constructed. Three network centrality measures were employed for analyzing the old and new maps, namely, degree, closeness and betweeness centrality measures. In the degree centrality profile of both maps, there is no discernable pattern to be observed such that the metric does not serve as a good differentiator or descriptor of the evolution of the road network of Manila. On the other hand, the latter two metrics proved to be better quantifiers. In the closeness centrality profile, we saw that in 1908, most of the nodes are closed to each other such that regardless of the starting point, one can easily access other locations. On the other hand, in the 2018 map, the presence of more roads gave rise to many more shortest paths in between roads such that in order to reach a node, one has to pass many more edges. Finally, much difference in the betweeness centrality is observed over the 100 years. In the old network, most of the nodes are utilized most especially the three bridges connecting the north and south regions of the city. In 2018, with the development of the northeastern region and the availability of other transportation means i.e. trains, nodes with high-betweeness values moved away from the geographical center.

Because we only considered two road networks, the information we can derive on the evolution of the city's network is still very coarse. For future work, we try to incorporate more timestep (more historical maps) in order to understand direction of growth of the network. Also, we might also look into the robustness of the city road network. Studies such as this one aims to contribute towards the growing literature on a quantitative analysis of urban systems, with the aim of developing strategies for further growth and adaptation in the cities.

ACKNOWLEDGMENT

We are grateful to the Filipinas Heritage Library for providing the historical maps from which the study has been based on. MTC acknowledges the financial support from the Advanced Science and Technology Human Resources Development Program (ASTHRDP) of the Science Education Institute (SEI), Department of Science and Technology (DOST).

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