POI VizNet: New QGIS Tool to construct Visibility Networks in Cities

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Abstract

Network science and graph theory offer attractive models to describe urban phenomena and examine cases of urban planning and design. However, none of the existing network analysis tools consider simultaneously human visual perception and locations of urban activities. In this paper we introduce POI VizNet, a new QGIS plug-in that constructs various 2-dimentianal undirected graphs of unobstructed lines of sight. The plug-in integrates an increasing amount of available GIS-based data of Point Of Interest (POI) and visibility into one readily accessible analytical framework. Graphs are created between two types of decision points during urban travel – street intersections and POIs, origins, and destinations of travel, by connecting these potential observer's decision locations in an open space between buildings. In addition, POI VizNet provides advanced options to build graphs using a predefined viewing distance and perceptual perspective. Visibility graphs are constructed and visualised as new layers in QGIS and delivered as network files suitable for further exploration, analysis, and visualisation in various network software packages.

1. Introduction and Background

1.1 General Cities analysed as Graphs

For decades, relationships between urban objects and locations are systematised by mathematical graphs and studied by the use of network science (Marshall et al., 2018; Agryzkov et al., 2017). Graphs are constructed from a set of vertices (nodes) and a set of edges (links). These are denoted as a pair G (V, E) where V is the set of vertices, V = {v1, v2, . . . , vn}, and E is the set of edges (see e.g., Gross and Yellen (1999); Barthelemy (2010) for comprehensive introduction to graph theory). A graph can be represented in many ways, the two most common is an adjacency matrix A, where:

$$A_{i,j} = \begin{cases} 1 & \textit{if the vertices } u_i \textit{ and } v_i \textit{ are connected,} \\ 0 & \textit{otherwise} \end{cases} \quad (1)$$

and an adjacency list, which is an array A of separate lists. Each element of the array A_i is a list, which contains all the vertices that are adjacent to vertex i.

According to the meaning assigned to nodes and links, different types of spatial representations can describe various urban networks. Urban studies literature provides a wide range of representations where nodes in the graph demonstrate the relationships between such urban elements as street intersections, street segments, street names, continuity or axiality of the streets, as well as plots, parks, buildings, transportation systems, neighbourhood, landmarks, etc. (Agryzkov et al., 2017; Barthelemy, 2015). In addition to urban elements, nodes can bear characteristics of human behaviour, such as travel decision points. For their part, relationships between nodes in the graph can vary from representation of direct connections or distances (as in planar graphs) to route choices (Boeing, 2020; Warren et al., 2017).

1.2 Encoding Spatial Information using Vision

There is a growing overlap between graph-based models used in behavioural sciences and urban studies (Natapov et al., 2023; Natapov and Grinshpun, 2020; Natapov and Fisher-Gewirtzman ,2016). In the field of behavioural sciences, such models imitate mental representations of environments, while in urban studies they aim at identifying and describing structural properties of the built environment. These models are based mainly on vision, as visual properties are embedded in both the urban environment and human behaviour (Kim, 2009; Lu et al., 2017; Jiang et al., 2002). Unlike the simple notation of distance or location, visibility graphs (VG) account for cognitive complexity involved in urban life. Visibility is an important determinant of urban vitality; visuospatial characteristics play a central role in navigation performance (Wang et al., 2014). Especially, such tasks as wayfinding, search and exploration in an unfamiliar urban environment are based on the human sense of sight as a generative feature for shaping spatial memory and behaviour (Wiener et al., 2009).

1.3 Growing GIS-based POI Data

Most of the existing urban graph methods consider only street networks and ignore other aspects of the built environment. However, the ability to evaluate the attractiveness of opportunities is a key concept in urban studies (Yue et al., 2017). Depending on the social, economic, or cultural context, it might be access to drinking water (Yang et al., 2013) to healthcare (Luo and Wang, 2003), to jobs (Hu, 2013), retail, landmarks, or other urban assets. All these could serve as origins and destinations and accommodative centres of urban activities (Bielik et al., 2018). Over the years, a range of street-related software tools have been developed, e.g., OSMnx (Boeing,2017), sDNA (Chiaradia et al., 2012), Depthmap (Turner, 2007), Mindwalk (Figueiredo,2005), GIS Axwoman (Jiang et al.,1999), Axman and WebMap (Dalton,1988) and Confeego and iVALUL from Space Syntax Ltd. However, analysing street network connectivity alone without considering additional information does not present the whole picture of the urban realm. As an increasing amount of geographic data in geographical information systems (GIS) becomes available, readily accessible tools are needed to integrate point of interest (POI) locations into spatial analysis techniques.

Some of the software, such as UNA toolbox (Sevtsuk and Mekonnen, 2012) and Place Syntax Tool (Ståhle et al., 2005),

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include an additional urban element - buildings. But these approaches have remained simplified, as none of the existing tools consider human visual perception, while vision and visibility are one of the major features influencing spatial cognition and behaviour – about 90% of information transmitted to the human brain is visual.

1.4 POI VizNet

In this paper we introduce an open-source toolbox POI VizNet (Figure 1). POI VizNet is based on visual access, a basic cognitive property of humans, as a key factor for the analysis. The tool is developed in Python as open plug-in for the QGIS[1] platform, compliant with open standards and free to use for any purpose. QGIS, previously known as Quantum GIS, is a free and open-source platform desktop GIS application. It offers managed plug-in installation, supports automation with macros and scripts, and more advanced customization with its Python API, that gives access to useful packages developed by the wider Python community.

Figure 1. Toolbox logo2

QGIS is a natural platform for the proposed tool, with its ability to handle geographic and geometric data associated with attribute information. It also has an ability to easily support viewing and editing, to perform spatial, mathematical, and statistical calculations and to visualise the results. The POI VizNet plug-in is available for installation and update via the ‘Plugins Manager’ tool of QGIS, making it easily accessible and maintainable to any QGIS user.
Unlike formerly developed urban network tools that operate with street network alone, POI VizNet includes additional urban element – POI – locations of predefined points of interest. Therefore, any specific entrance to the building, activity or amenity on the same street can create different results in terms of visual attractiveness. Toolbox’s units of analysis thus become both urban tissue and POI, allowing to create different visibility graphs and to compute network measures separately for each urban element. This enables accounting for a particular location, building, entrance or land use throughout the visibility network, neither of which is addressed in the existing analysis approaches.

2. Toolbox Functionality

2.1 How We represent Visuospatial Properties of Urban Environment?

To create visibility graphs we encode urban environment by two types of nodes. These nodes are potential decision points along available urban routes. The first are navigational decisions within the street network: street junctions (Figure 2a). The second are locations of POI, any location instances that the toolbox’s users may find useful according to their aims - buildings, entrances, land parcels, stations, eating and drinking facilities, accommodation, commercial services, retail, attractions, sport, leisure, entertainment, education, health facilities, public infrastructure, etc.[3] (Figure 2b).

[1] Qgis.org
[2] Current POI VizNet (POI Visibility Network). release: https://plugins.qgis.org/plugins/poi_visibility_network

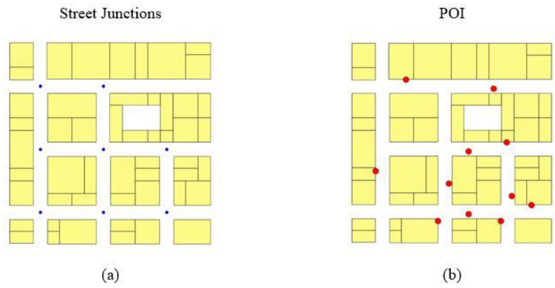

Figure 2. Two types of decision points (or observer/traveler location) within the urban layout: (a) street junctions; (b) POI (in this case point-based features).

These two types of nodes are connected in different constellations by lines of sight (links in the graph) if they are visible from each other in the space between the buildings. Building footprint polygons serve as geometric constraints - we consider open space as space available for views experienced in any transport mode - pedestrian, vehicle, or cycling. Therefore, the created graph illustrates hypothetical visual trajectories of a person looking for a particular POI in the city. The graph is called Integrative Visibility Graph (IVG) as it incorporates both navigational and functional aspects of the city (Figure 3a). IVG examines connectivity of the particular location, i.e., predefined POI within the street network.
In addition to IVG, the current version of the toolbox offers two separate modules of analysis corresponding to two additional types of visibility: Street Network Visibility Graph (SNVG) - creates visual connections between decision points of the street network, i.e., street intersections (Figure 3b), and Point of Interest Visibility Graph (POIVG) - creates visual connections between POI that are visible from each other in a given building arrangement (Figure 3c).

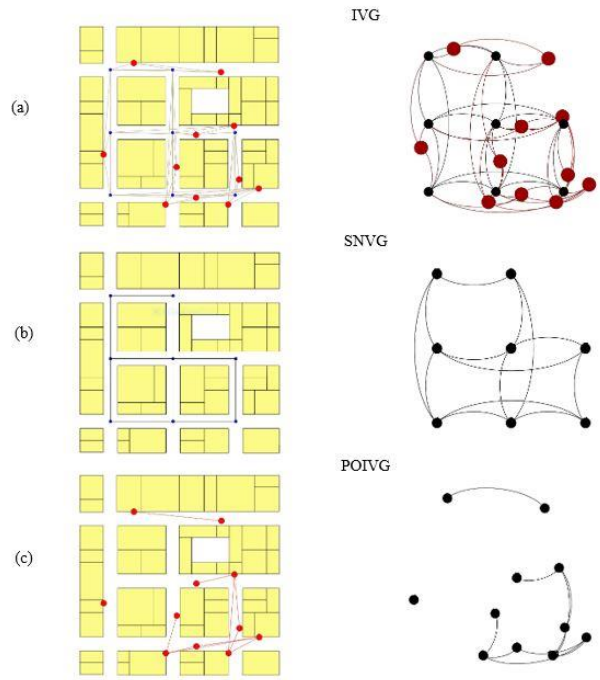

Figure 3. Three types of visibility graphs available in POI VIzNet in geo-referenced and curved visualizations: (a) Integrative Visibility Graph (IVG); (b) Street Network

[3] https://wiki.openstreetmap.org/wiki/Map_Features

Visibility Graph (SNVG); (c) Point of Interest Visibility Graph (POIVG).

2.2 The Toolbox’s Workflow

Figure 4 presents POI VizNet’s logo and a menu, where each visibility module is accessible individually. Figure 5 presents a typical implementation flow of the toolbox consisting of the six steps. At the first step, input data is prepared as described in section 2.3 (Figure 4c in the menu). Second, the user chooses suitable nodes for the graph type she wishes to create – SNVG, IVG or POIVG (Figure 4a) and whether to create links (Figure 4b). Third step (Figure 4d) is optional - the user can choose advanced parameters, such as viewing distance or perceptual effect (section 2.5) or continue without them. Fourth is the main step when the visibility graph between the chosen locations is constructed and displayed on the QGIS map canvas. Then the graph data file is created for further analysis, which is done in QGIS or in the network software, for instance such as Gephi[4] (Jacomy et al., 2009) intended for graph and network analysis. Finally, in the last step, network analysis results are visualized in QGIS and made available for further spatial queries within it.

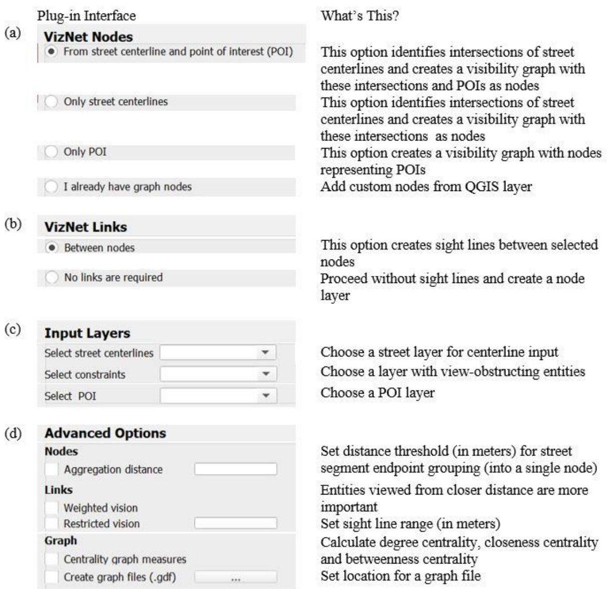

Figure 4. POI VizNet menu: (a) nodes for different analysis modules; (b) link options; (c) input layers; (d) advanced distance options.

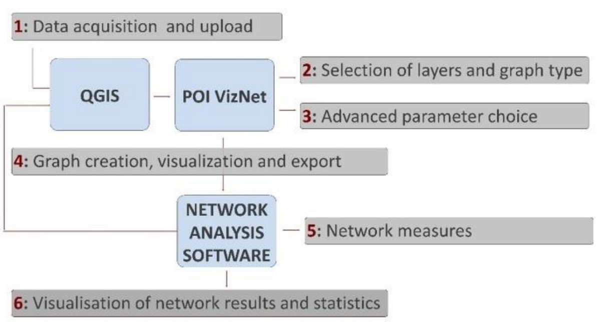

Figure 5. POI VizNet operational steps.

2.3 Pre-processing of the Input Data

To create visibility graphs in POI VizNet three input layers are required – streets (centrelines), constraint (building footprints) and POI. These are GIS shape vector layers, polyline, polyline/polygon, and point/polyline/polygon, respectively. The second layer, building footprints are accepted in the plug-in either as polylines or polygons. In case of polyline, the tool converts them automatically to polygons. POI VizNet can be employed only after the required layers are loaded in the QGIS map canvas. Figures 6a, 6b and 6c demonstrate a sample of the input data. For IVG and POIVG, all three layers are necessary, and for SNVG, no POI layer is required.

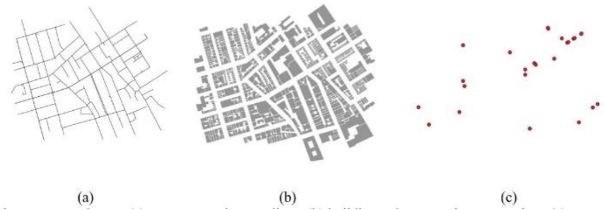

Figure 6. Input layers: (a) street network centrelines; (b) building polygons - view constraints; (c) POI. Courtesy © OpenStreetMap.

2.3.1 Georeferencing of Coordinate Systems: To perform metric calculations, POI VizNet needs to make sure that all the layers are projected in the same coordinate system. Thus, at the beginning of the run all the input layers are converted to WGS 84/Pseudo-Mercator coordinate system (EPSG:3857), a standard international Cartesian map projection system, using QGIS datum transformation.

2.3.2 Intersection Identification: The next important step of data preparation is identification of street intersections (nodes in graph) that serve as initial decision points within the urban environment. These nodes are derived from the street centrelines. To identify these, POI VizNet uses GIS ‘quadtree’, a tree data structure for operative search of nearby points. When more than two lines are touched, the algorithm verifies that a node exists on the intersection (Figure 7a). When only two segments are touched, it eliminates a node at their intersection, as this is a drawing error (Figure 7b).

Figure 7. Street intersection node identification and pre-processing: (a) node at the shared location of three segments; (b) no node at the intersection of two segments.

[4] https://gephi.org/

2.3.3 Intersection Aggregation: In some mapping styles intersections are shown by a pile of segments, which do not meet in one point (Figure 8a). To identify a real point of the intersection and to improve layer accuracy, we apply a spatial clustering correction. Correction mechanism aggregates different segments' endpoints into one node (Figure 8a). First, we create a new layer that measures distance from each intersection to the ten closest neighbouring end points, including the source (Figure 8b). Then each node is multiplied ten times with the associated distances. For example, intersection #1 (Figure 8b) is duplicated ten times – first with a distance of zero (the source intersection itself) and with the following closer distance. Then, all intersections that exceed a 20-meter distance threshold are deleted from the newly created layer (Figure 8c). 20-meter threshold fits best OpenStreetMap (OSM), the potential open-source data for the plug-in. In addition, all the nodes having duplicated identical locations are deleted. Accordingly, a new intersection layer is created presenting the centre of all group intersections and associated IDs.

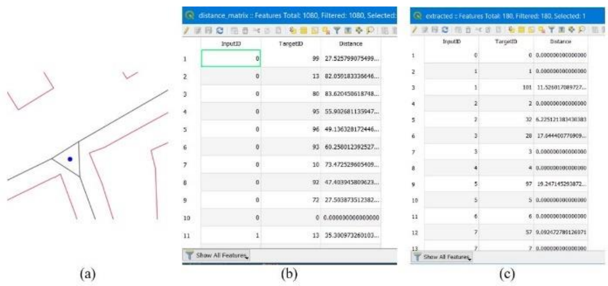

Figure 8. Intersection aggregation: (a) illustration of the need for aggregation; (b) distance matrix; (c) applying clustering mechanism as a centroid of all the end points.

In the plug-in there is an option to customise distance threshold relevant to user input layer (aggregated distance in Figure 4d). Depending on the map drawing style and accuracy various radiuses could be suitable and adjusted by users. Figure 9 shows results of an aggregation trial according to the thresholds of 20m, 30m, 40m and 50 meters for a map originated by UK Ordnance Survey. In the first version of the plug-in, we keep the distance fixed on 20 meters.

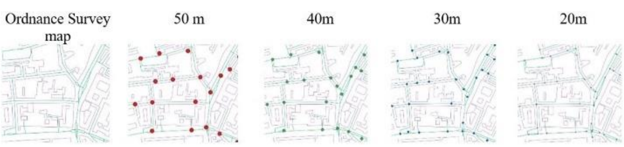

Figure 9. Test of different aggregation radius. Background © Crown Copyright and Database Right 2015. Ordnance Survey (Digimap License).

In addition, there is an option to input customised shape layer of the nodes, which users can prepare in any suitable drawing or analytic software (Figure 4a).

2.3.4 POI Transformations:
POI VizNet deals with any geometry of POI – point of interest that are inputted as a point, a polyline, or a polygon. However, visibility graphs are built only between points, so polylines and polygons should be transformed into geographically positioned points according to the feature's centroid (Figure 10a and 10b).
Additionally, in many datasets POIs are marked inside the polygon of the building. Consequently, extra step is required for the pre-processing of these POIs into nodes suitable for the visibility graph construction (Figure 10c).

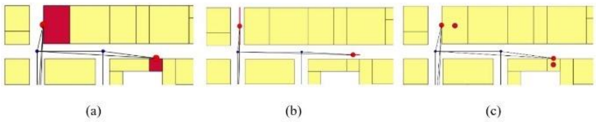

Figure 10. Identification of the POI nodes and necessary transformations (a) POI drawn by another geometry - as red polygons; (b) as red polylines; (c) POI drawn inside the building polygon and its projection, a point outside the building.

Building footprints serve as visual boundaries (constraints) for views, and we consider only the views available in the open space between the buildings. We assume that each POI is most likely to be located outside the building in front of the façade that lies closest to the street (Figure 10c). Therefore, inner POIs are projected outside the façade according to the following technical steps:

1. Creation of two new layers – one consists of POIs located inside buildings, and another with POIs located outside buildings.
2. Creation of an additional layer from the street network. In this layer, the street network segments are broken into 5-meter sub-segments with temporary nodes at the end of each new segment.
3. Creation of a new polyline-based layer that connects all the POIs inside buildings with the closest street segment created in stage 2.
4. Implementing a 1-meter buffer around the buildings to keep POI outside the contour.
5. Final projection of the node is created at the crossing of the buffer from stage 4 to the line layer created in stage
6. Merging the newly created node layer into the 'POI outside the buildings' layer.

2.4 Visibility Algorithm

The main stage of POI VizNet is sight line construction. This stage is based on Natapov et al. (2013) that used an algorithm written in MathWorks, MATLAB and on Jiang et al. (2002) that introduced visibility-based graph schematization of street networks.
First, we build lines in a newly created line-based layer. These lines connect each point on the point-based layers (intersection nodes and/or POI nodes) to all other points in the boundaries of the analysed space (Figure 11a and 11b).

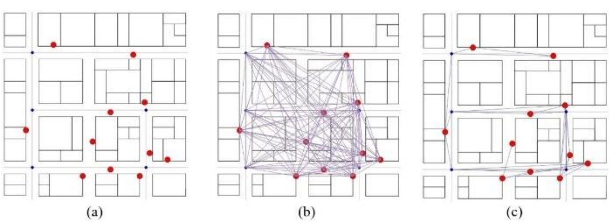

Figure 11. Construction of visibility lines: (a) before the construction - POI in red, road intersections in blue; (b) all possible view lines between the two types of nodes disregarding buildings; (c) refined view lines taking into consideration the building boundaries (constraint).

If advanced viewing distance limit is applied (Figure 4d), the resulting lines are restricted according to this predefined threshold. On the next step, the plug-in uses a QGIS processing tool called 'Extract by Location'. This tool performs spatial queries allowing to select features in a given layer by their spatial relationships (intersect, contain, touch, disjoint, etc.) with features from another layer[5].

2.5 Advanced Distance Options

Real-world settings consist of a wide range of physical properties of viewers and environments. These include distance, size, color, shape, texture, pattern, complexity of the viewed elements, their static or dynamic position, atmospheric conditions, angle of observation, etc. (Wang et al., 2014; Gret-Regamy et al., 2007; Shang and Bishop, 2000). However, POI VizNet is typically applied to dense urban conditions, where the focus is on the line of sight, as the most influential feature. We introduce two advanced options to broaden the viewing distance options. While the default mode of the plug-in is unlimited vision - when the lines of sight are created at any distance for mutually visible locations - user wishing to consider more realistic parameters of visual perception can choose:

1. Restricted vision. This option defines the distance on which visual connections are created (Figure 4d). This option allows to incorporate metric distance in one framework with topological properties of visibility. For instance, a rule of thumb of '400-meter rule' could be employed. This value is proposed in Mehaffy et al. (2010) as the maximum spacing of main thoroughfares that empirical observations show in traditional pedestrian governed urban fabric.
2. Weighted vision. This option accounts for the effect of the distance on human perception. Entities viewed at various distances will have different perceptual impacts: for instance, closer entities might look more important. To capture this perceptual phenomenon, we add weights associated with the length to newly created links (lines of sight). They are calculated as follows:

$$\frac{1}{d^2} \quad (2)$$

where d is the metric distance between nodes.

2.6 Centrality Measures and Data Output

At the end of the run, two new layers of sight lines and nodes are visualised in QGIS. The 'Sight line' layer consists of the line geometries, with attributes: ID, length, and weight (if advanced option of weighting is implemented). A layer of nodes consists of two sub-groups (POI in red and street nodes in blue), and an attribute table summarizing their coordinates and ID.

A graph output folder must be determined prior to the run (Figure 4d). In this folder POI VizNet stores the created graph and two new layers. The graph is stored in the format of Geographic Data File (GDF), which is used by GUESS (Graph Exploration System) - visualization tools displaying networks and mathematical graphs.

To evaluate the level of attractiveness of urban locations, network centrality measures are used (Freeman,1979). Resulted GDF is suitable for centrality exploration in any network software package, or these measures can be calculated within the plug-in (Figure 4d). POI VizNet centrality measures are based on NetworkX[6], a Python package for the creation, manipulation, and study of the structure, dynamics, and functions of complex networks (Hagberg et al., 2008). These include degree centrality, closeness centrality, and betweenness centrality (Wasserman and Faust, 1994; Freeman, 1979.

2.7 Implementation Examples

Research has demonstrated that OSM data are geometrically accurate and up-to-date, particularly in urban areas (Barrington-Leigh and Millard-Ball, 2017; Zhou, 2017). Using this reliable OSM data, of an area in Bloomsbury, a district in the West End of London, UK, we demonstrate in this section a range of POI VizNet features. Figures 12a, 12b and 12c present three options of the graph construction available in the plug-in. These are SNVG, IVG (in this case of all building polygons) and POIVG (in this case with food establishments found in the area), as well as the resulted number of corresponding nodes (# N), links (#L) and POI. For graph exploration we use several layouts available in Gephi network package. In Figure 12a, SNVG is shown in the force-directed layout, when by assigning forces to edges and nodes according to relative positions, their motion is simulated.

In Figure 12b, IVG is shown in the same layout with calculation of modularity measure. Modularity is a measure used in optimization methods for detecting community structure in networks or graphs. It is designed to measure the strength of division of a network into modules, also called groups, clusters or communities (Brandes, 1994). In Figure 12c, POIVG is shown in the circular layout that displays the distribution of nodes and their links on an imaginary circle.

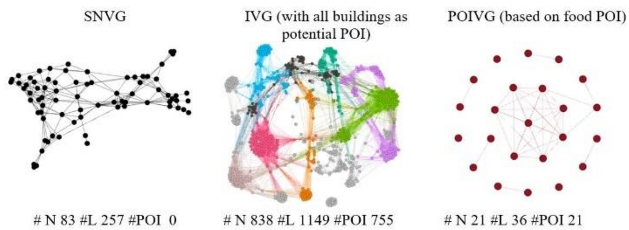

Figure 12. (a) SNVG; (b) IVG with all buildings as POI laid out by the modularity; (c) POIVG in the circular graphic layout.

Figure 13 shows several tools for quick characterisation and visualisation of the graphs using both POI VizNet and network analysis packages. For instance, Figure 13a finds the shortest path in the geo-referenced and non-georeferenced layout of SNVG. Calculation and visualisation of the shortest path can help us to understand a sequence of views in the studied built environment. Figure 13 shows a detail of the IVG graph based on the 50 meters viewing threshold. Intersections are shown in black and potential POI locations are in red. This visualisation demonstrates how POI from the same street are grouped around a certain intersection. Figure 13 is a detail of the graph with the weighted links. Thicker links stand for the closer location, as described in section 2.5, and reflect the perspective perception of these places.

[5] https://qgis.org/api/qgsalgorithmextractbylocation_8h_source.html

[6] https://networkx.org/

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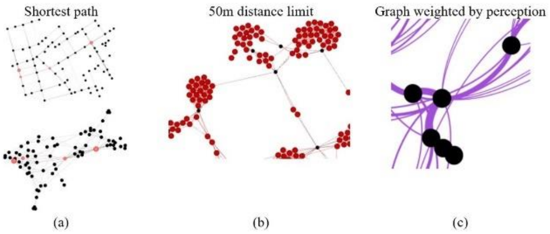

Figure 13. Study of graphs: (a) short path visualization on SNVG; (b) distance limit, a detail of IVG with all the buildings; (c) links differentiated by weights.

3. POI VizNet: Discussion

3.1 Significance of Networks

In contrast to other vision-oriented analysis methods, such as local isovists or view shields (Kim et al., 2019; Benedikt, 1979), POI VizNet translates a city into network-based structure. Network characteristics are global, and therefore they offer a more nuanced picture of urban realm, unique for each building or each POI. Analysing visual patterns with methods from complex network science, we suggest a new link between urban social processes, spatial cognition, and physical theories. A wide range of measures, developed in network and graph theories, could assist in understanding urban evolution – networks' structure, their density, resilience, connectedness, hierarchy, modularity, or clustering works' structure, their density, resilience, connectedness, hierarchy, modularity or clustering (Arcaute et al.,2015; Barthelemy,2015; Newman,2010), though not discussed here in details.

3.2 Limitations and Further Development

POI VizNet is a long-term project currently managed by the School of Architecture, Building and Civil Engineering at Loughborough University UK. The toolbox is distributed in open- source form. Each download comes along with the latest source code, and we invite all interested scholars to contribute to the further development of the tool. The current release only covers a fraction of possibilities and has inherent limitations arising from the representation method and computational power. First, for the sake of simplification, we treat any environment as two dimensional, and refer to visibility as mutual, i.e., the resulted graphs are undirected. In the future, we plan to add 3D, directional viewing and a wider range of psychical properties impacting visual perception. These could include size, colour, shape, texture, complexity or transparency of the viewed urban objects and atmospheric conditions. Even though the representation of the built environment via several simple elements – nodes, edges, buildings, and POI – may appear limiting at times, a thoughtful use of additional QGIS features seems to offer a rather powerful framework for investigating various research and practice questions.

Second, current version of the toolbox has limited computational power capability. Due to the complex pre-processing, aggregation and calculation processes, the analysis is performed only on size limited areas in a range of a small neighbourhood. In the future, we plan to enlarge POI VizNet powers to enable graph construction that covers entire cities. View distance limitation is recommended while working with bigger cases.

Next plug-in's shortcoming is related to data quality and availability. Potential issues with identification of the intersections and POI locations might occur due to insufficient or defective data sources or mismatch between different formats. As described in section 2.3.4, the plug-in implements complex transformation operation re-projecting inner POI outside the buildings. Apparently, this operation is not perfect and could produce the result that differs from the real location of the amenity. It is only the most suitable simplification that assists to describe how POI is visible from the street, when the entrance address is not mapped correctly. Should a user wish to compute the correct location of the POI, the manual edits of the address are required. Finally, section 2.3.3 describes the process of intersection aggregation that addresses challenges of maps' inconsistency in intersection representation. We allow users to define needed threshold according to her own data. Default option is a 20-meter threshold, when all the intersections in this radius are inevitably aggregated to one point. However, 20 meters is not an optimal choice for all existing urban cases.

3.3 Contribution – POI VizNet Potential Users and Applications

POI VizNet combines three historically disconnected approaches - graph analysis, land-use analysis, and visibility analysis, and thereby opens up new empirical ground for these fields. It integrates POI, visual perception, and network analytics in one single platform. It expands QGIS with new behaviour-oriented exploratory functionality and allows to explore urban environment using interactive visual exploration, as well as to deepen into further statistical analysis, inquiry of individual measures and locations, identification of network core, hotspots or clustering. Planners, architects, and scholars of the built environment are given a unique tool to incorporate a basic human ability, vision, in their practice. Such practice will rapidly grow with the increasing availability of geospatial and imagery data.

The research community can use POI VizNet in simulations that evaluate wayfinding, pedestrian risks, and route search efficiency. Such simulations will investigate interaction between cities' spatial and cognitive features, e.g., how individuals interact with the urban space, and how this space constantly evolves and transforms from the bottom up in response to behavioural patterns.

City performance depends on human behavioural routines - thus, POI VizNet is also highly relevant to the practitioners' community. It contributes to more informed design and assists in understanding factors determining and driving emergence of new amenities or new building uses within certain morphological conditions.

POI VizNet is useful for authorities and stakeholders dealing with the issuance of zoning and building permits for new uses that would alter urban fabric. The use of the new toolbox can prevent withdrawal of pedestrian-oriented commercial uses to the secondary streets, as well as prevent excessive automobilization of city's main streets happening in many planned, modern cities worldwide. Therefore, POI VizNet promotes neighbourhood vibrancy and creates sustainable urban context with mix use desirable for pedestrians.

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