

A heuristic spatial algorithm for generating fine-scale infrastructure distribution networks

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January 10, 2017

Summary

Understanding the spatial connectivity of infrastructure distribution networks that connect assets to buildings is important for the fine-scale spatial analysis and modelling of the resource flows within cities. However, rarely are spatially explicit representations of infrastructure networks available for such analysis. This paper presents a heuristic spatial algorithm that can generate plausible spatial distribution infrastructure networks that extract both the underlying geometry and also the topology of the network. Application of the algorithm is demonstrated via the generation of the electricity distribution network between low-level substations and residential buildings for Newcastle upon Tyne.

KEYWORDS: Infrastructure networks, spatial heuristics, fine scale.

1. Introduction

Modern cities consist of spatially and temporally complex networks that connect urban infrastructure assets to the buildings they service (Moss and Marvin, 2016). Critical infrastructure networks include transport, electricity, water supply, waste water and gas, all of which play a key role in the functionality of modern cities (Murray and Grubestic, 2007). The topology and geometry of such critical infrastructure networks is required in many research applications such as smart-city sensing and metering studies of local energy distribution and energy flows. However, it is rare for information on the spatial layout and configuration of infrastructure distribution networks to be available (Fu *et al*, 2005). Thus, there is an urgent need for approaches that can generate, at very fine spatial scales, plausible distribution networks from infrastructure assets to the buildings they service. In this paper we present a spatial heuristic algorithm that can generate plausible synthetic spatial network representations of infrastructure connectivity from assets to buildings for use in cities-based research.

2. Spatial heuristic infrastructure network generation algorithm

The developed algorithm works on the assumption that the location of existing infrastructure distribution assets (e.g., electricity substations) are known, along with either the spatial footprint or centroid of buildings. It is also assumed that the road-network for the study area is available (Figure 1).

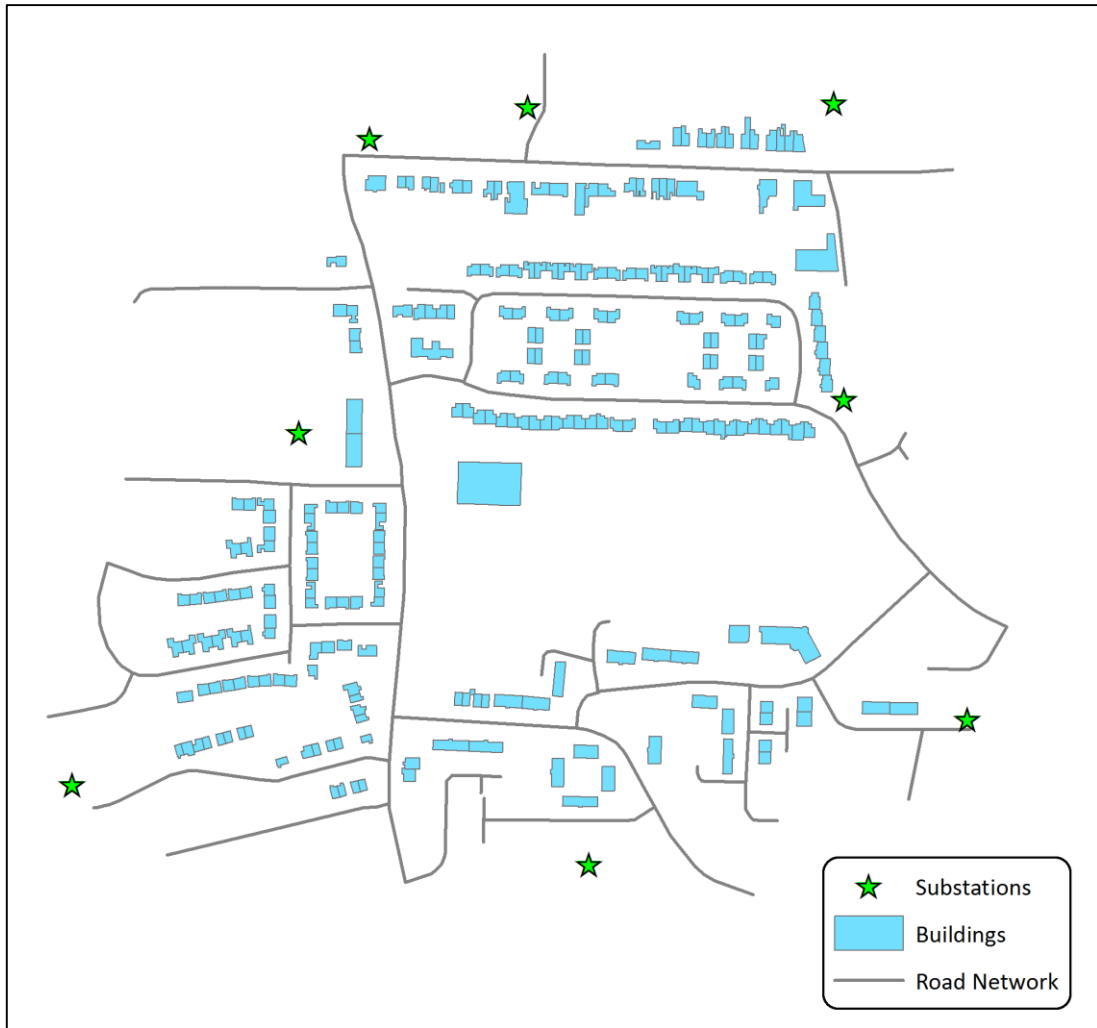


Figure 1. An example area in Newcastle upon Tyne showing building footprints and electricity substations (Contains OS data © Crown copyright and database right 2017).

The algorithm is based on the assumption that each individual building is served by one and only one distribution asset (substation). Moreover, we assume that topologically touching buildings or those within a specified proximity tolerance (e.g., 5meters) form a union building footprint which are served by the same distribution asset. In order to assign a building or union group of buildings to an infrastructure distribution asset it is assumed that the corresponding infrastructure network has been constructed spatially along the existing road network. The assumption is that infrastructure pipes and cables are generally buried at accessible locations relatively close to the road-network (Larkevi and Holmes, 1995). The centroids of buildings (including union group building footprints) and the location of the distribution assets are used to generate a *base network*; edges are connected from the building centroids and the distribution asset locations to the road network. In the case of a union group of buildings, the centroid of each individual building that forms the union group has an edge created to the road network to ensure that they are assigned/connected to the same distribution asset (Figure 2).

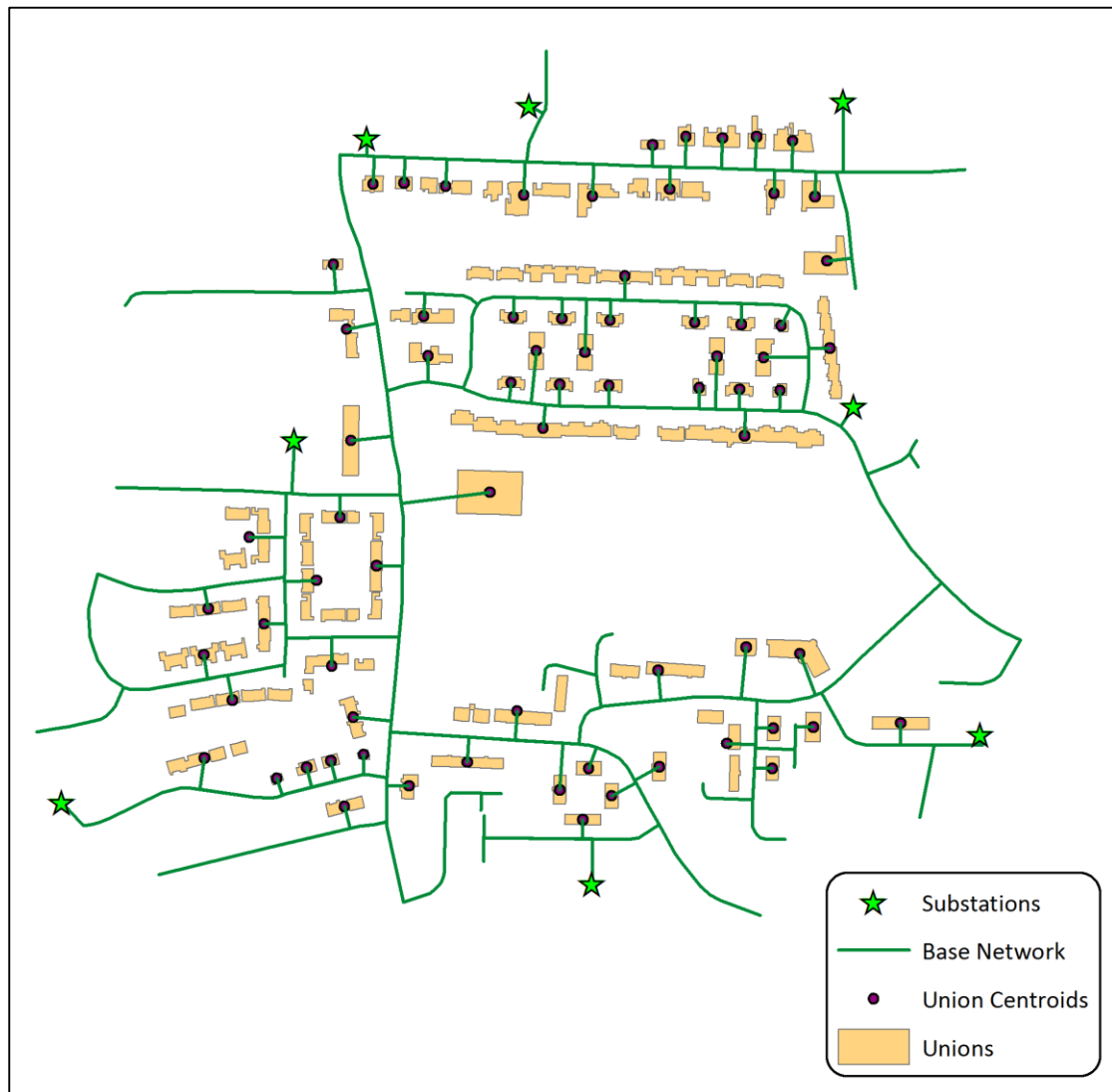


Figure 2. *Base network* generated by connecting centroids of unions and substations to the road network (Contains OS data © Crown copyright and database right 2017).

Although this generation of the base network is straightforward, its time complexity is $O(n^2)$ and results in large computational overhead when generating networks for large urban areas. In order to address this issue, we spatially constrain the possible distribution assets that a building or union group of buildings can be assigned/connected to. In order to do this, we use distribution asset points to triangulate the entire area and then work out which triangular facet each building or union group of buildings fall within. We then constrain the potential servicing distribution assets to be those that form the nodes of the triangular facets that topologically touch the primary triangular facet that the building or union group building falls within. For example, in Figure 3, the highlighted building falls within triangle 5, and triangle 2, 3, 4, 6, 7 are touching triangle 5. Therefore the potential distribution assets for the highlighted building are 1, 2, 3, 4, 5, 7 and 8.

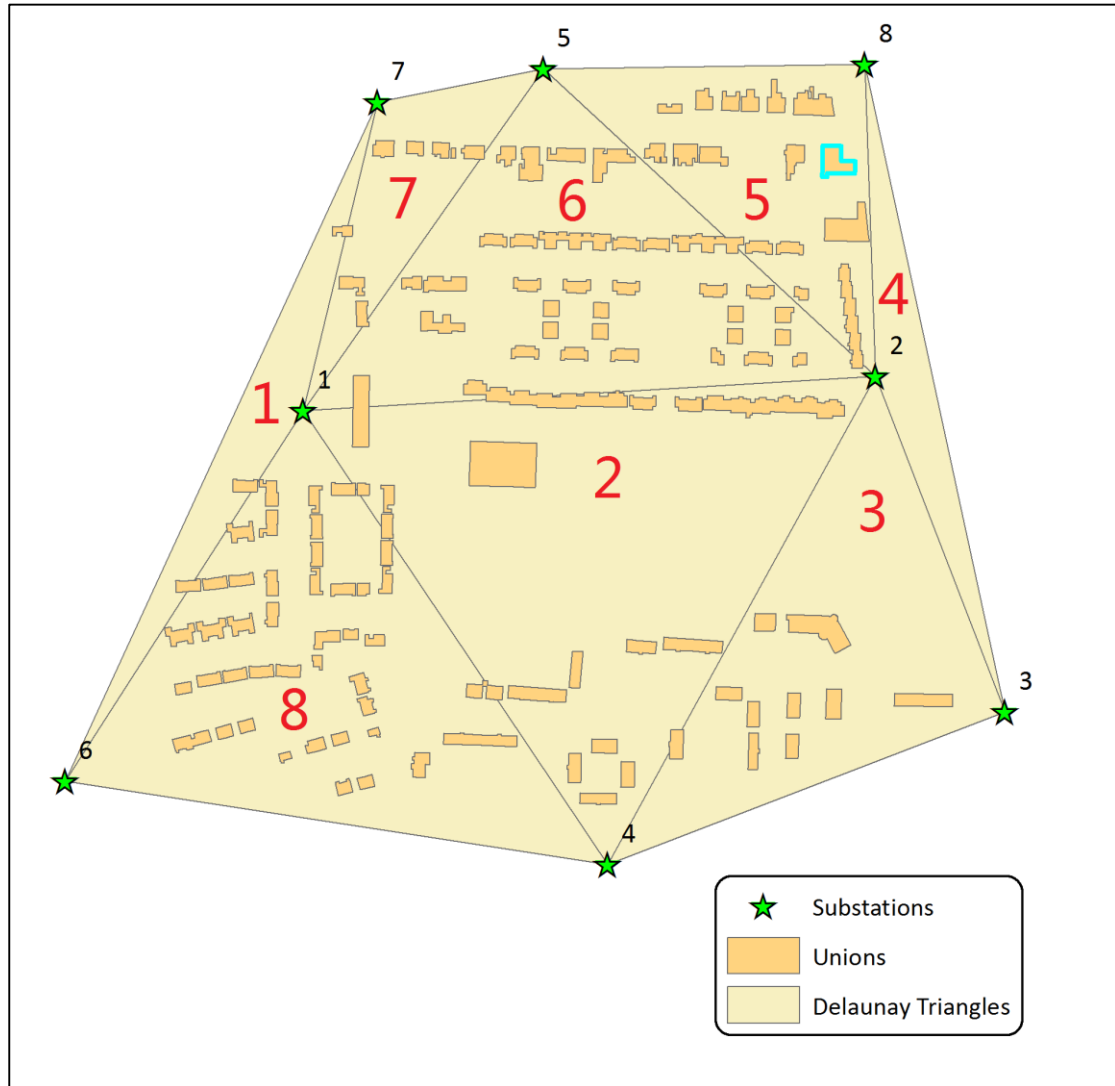


Figure 3. Using Delaunay triangulation to constrain the choice of potential substations
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Once a first pass assignment of buildings to infrastructure distribution assets has been performed, the spatial and geometry infrastructure network connecting buildings and the infrastructure distribution asset they are serviced is derived. The stages involved in this are demonstrated in Figure 4, where there is a road network, one substation and eight buildings. The algorithm proceeds as follows.

- (i) We start, as mentioned above, on the assumption that the electricity cables will be underneath or close to the road network (Figure 4(a)).
- (ii) For each building the nearest point of access to the road network is derived either with respect to its centroid or building footprint (Figure 4(b)). This is achieved by calculating the shortest distance perpendicular to the road network line segment and the building centroid/footprint.
- (iii) An edge is generated from each building to its corresponding access point on the base road network. This calculation is also performed for each infrastructure distribution

- asset assigned to service these buildings. At this stage each building and infrastructure distribution asset now becomes a node in the base network (Figure 4(c)).
- (iv) Starting at the infrastructure distribution asset, the shortest network path distance between the asset and the buildings on the base-network is calculated in order to generate a series of edges that form the network connection between them. During this stage, the algorithm employs a local search approach to move from one building to the next in order to try and maintain a logical structure for the evolving network (Figure 4(d)).
 - (v) The final stage involves merging all the shortest paths calculated in step (iv) and saving this as a new network instance (Figure 4(e)).

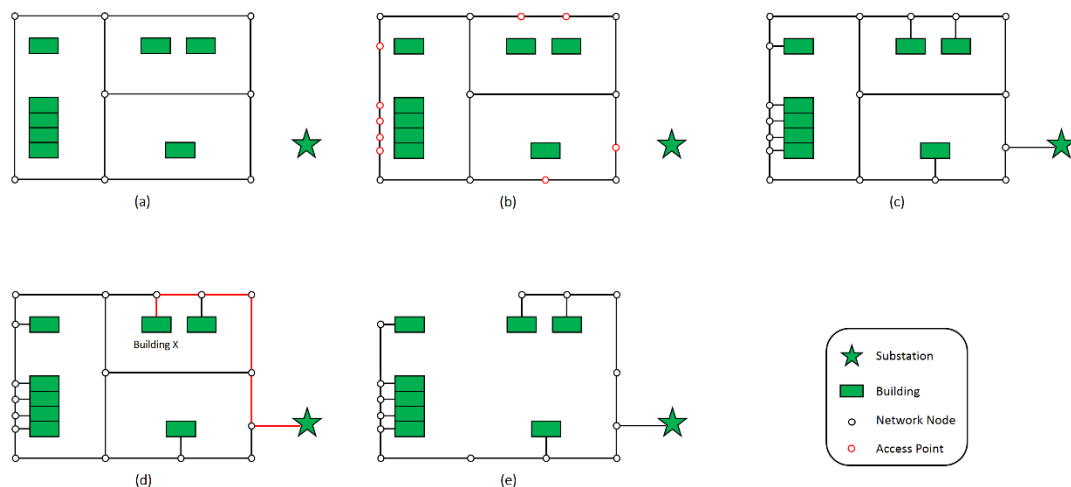


Figure 4. The steps involved in generating a local distribution network for a substation.

Figure 5 shows the electricity distribution networks generated for the area shown in Figure 1 using the algorithm. Each substation has its own distribution network, and each building is served by one and only one of them. The heuristic spatial infrastructure network distribution algorithm has been developed in Python using the NetworkX package (NetworkX, 2014) for the manipulation and analysis of complex networks. The developed algorithm employs the Infrastructure Transitions Research Consortium (ITRC) PostgreSQL/PostGIS National Infrastructure Systems Modelling Database (NISMOD-DB), for primary data extraction via a Python binding and generates network models that are written back to NISMOD-DB in the form of an instance of the ITRC interdependent network database schema reported in Barr *et al.* (2013).

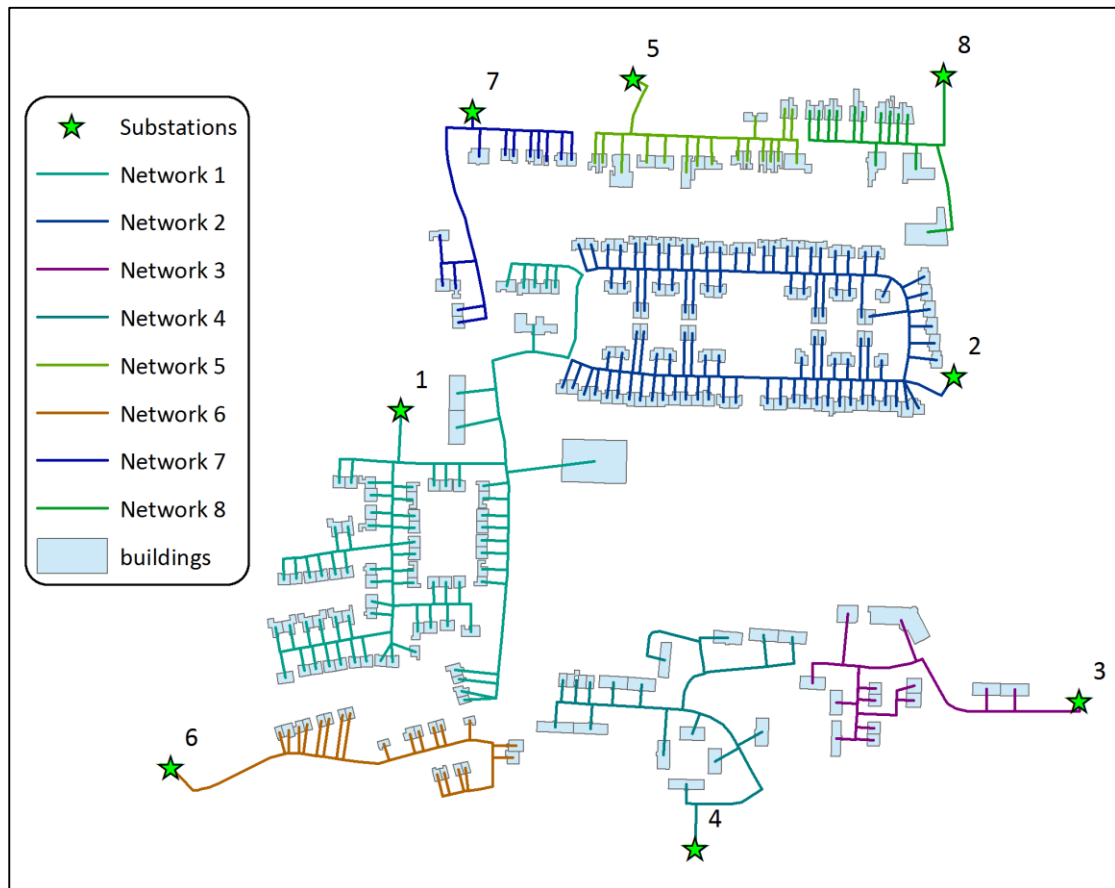


Figure 5. Electricity distribution networks for the area shown in Figure 1 (Contains OS data © Crown copyright and database right 2017).

3. An electricity infrastructure network application

To demonstrate the utility and scalability of the algorithm it was applied to generate the local electricity distribution networks for Newcastle upon Tyne. The input infrastructure distribution assets comprised all 11Kv electricity substations, identified from Ordnance Survey Points of Interest Data. Building footprints were obtained by filtering Ordnance Survey MasterMap topographic layer. The road network was obtained using Ordnance Survey Integrated Transport Network (ITN) data. All data was made available via the ITRC NISMOD-DB database system. In total, we selected 777 substations across Newcastle upon Tyne and the algorithm was applied across a broad range of different intra-urban morphological configurations of residential buildings, as well as to the whole of Newcastle upon Tyne. For the complete area, a total of 105,940 buildings were processed, creating 640 new local infrastructure distribution networks each with, on average, 165 buildings. Figure 6 shows the key stages in generating electricity distribution networks using the algorithm.

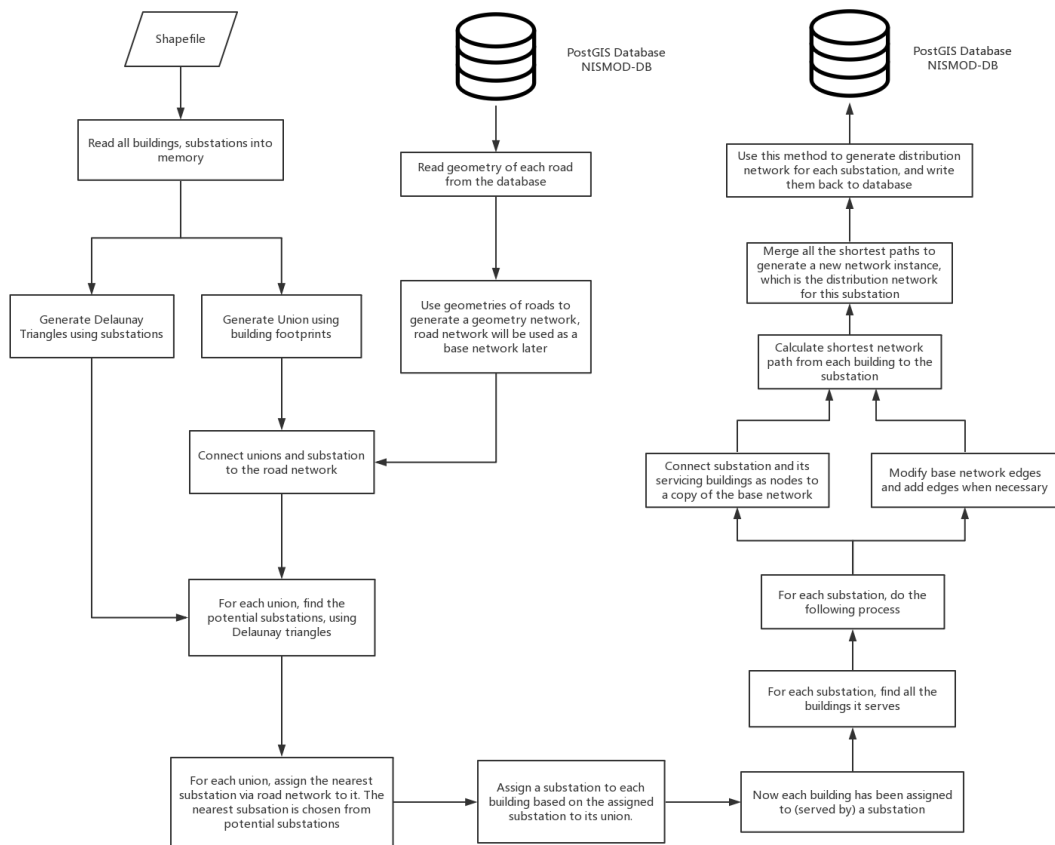


Figure 6. Flow diagram of generating electricity distribution network using the algorithm (Contains OS data © Crown copyright and database right 2017).

4. Conclusions

In many cities fine spatial scale infrastructure distribution networks do not exist for analysis and modelling purposes. This paper has presented a heuristic spatial algorithm to generate the topology and geometry of infrastructure distribution networks on the basis of the location of infrastructure distribution assets and neighbourhood buildings. The algorithm uses a basic premise that infrastructure distribution networks are collocated close to the road network. The algorithm has been tested on real data for Newcastle upon Tyne to generate electricity distribution networks. Future work will make the algorithm more flexible, to allow users to set the capacity of infrastructure distribution assets and also take into account different types of building activity (residential, commercial and industrial activity) as well as different infrastructure sectors.

5. Biographies

Qingyuan Ji is a PhD student in the School of Civil Engineering and Geosciences at Newcastle University. His PhD is developing spatial-analytical platform for the analysis, simulation and visualization of infrastructure networks within cities. Stuart Barr is Professor of Geospatial Systems Engineering at Newcastle University. Philip James and David Fairbairn are Senior Lecturers in Geographic Information Science at Newcastle University.

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