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Characterising the metric and topological evolution of OpenStreetMap network representations

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Abstract. OpenStreetMap (OSM) is a collaborative project to create a free editable map database of the world. This paper presents an analysis of the evolution of OSM street network representations. Three urban areas in Ireland were analysed where each evolves from containing little street network detail to a highly detailed street network. In order to characterise this evolution a number of metric and topological characteristics were computed. Some characteristics exhibited broadly similar behaviour in each region. This may be a attributed to similarities in the degree of contributor activity and intrinsic universal mapping procedures exhibited by contributors.

1 Introduction

Recent years have seen the widespread engagement of large numbers of private citizens in the creation of geographical or spatial data. These individuals often have no formal qualifications in performing a task which was traditionally reserved to official mapping agencies. This paradigm of user generated spatial data is commonly referred to as *volunteered geographic information* (VGI) [1]. The OpenStreetMap (OSM) project (`http://www.openstreetmap.org/`) was founded in the year 2004 and is one of the best known sources of VGI [2]. It is fast becoming an important source of spatial information in a variety of applications from transportation routing to emergency management [3]. The OSM Statistics page [4] on the OSM wiki displays up-to-date statistics regarding the OSM spatial database. As of January 2012 the database contains over 100 million way features which predominantly correspond to streets; in this article we use the term street when referring to streets, roads and other highway features. This page also shows that there are currently over 500,000 contributors registered with the OSM project. Contributors predominately capture geographical data through the use of *global positioning system* (GPS) or tracing over aerial imagery [5]. Spatial datasets which are available under OSM compatible free and open data licenses may be "bulk" imported into OSM. Examples include the Automotive Navigation Data donation of the entire street network database of the Netherlands

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and the TIGER network dataset in the United States. However, for many reasons, OSM discourages bulk importing unless it is supported by the larger OSM community [6]. With the recent announcement that Google Map Maker will now allow the general public to contribute to Google Maps, the VGI movement is set to go from strength to strength and play a key role in the supply of geographical data and services in the future [7].

Haklay [8] states that OSM contributors operate without central coordination or strict data frameworks; he states that this is a "highly unorthodox approach to mapping" which is not yet fully understood [9]. Such a lack of contributor coordination has also been noted in the community written encyclopedia Wikipedia [10]. In this paper we analyse the evolution of OSM street network representations in urban areas with the gaol of providing a new insight into the dynamics of mapping in OSM. This work offers a number of potential benefits. It may provide a platform for central coordination and the targeting of contributors with specific mapping tasks [11]. It may also allow us to evaluate if an area is mapped to a high standard without having to perform a comparison to ground truth such as that provided by an official mapping agency [2,9]. Finally, an understanding of the OSM evolution process may also allow us to predict if and when the OSM street network for a region has reached a desirable quality.

Given the huge importance of transportation networks to society it is no surprise that they have been of great interest to the scientific community. Researchers have studied the organisation of many forms of transportation networks including metro [12,13], street [14–21], rail [22,23], air [24] and sea [25] networks. Due to their spatial nature transportation networks are subject to many constraints which other forms of networks, such as citation networks, are not [26,27]. For example, the construction cost of streets is large and consequently streets tend to be of shorter length. This fact has resulted in many works which exclusively focus on transportation networks. These works can be broadly classified into two categories which we now discuss in turn.

Firstly many authors have performed studies which analyse the current state of transportation networks. Gastner and Newman [26] analysed and attempted to model three forms of spatial networks which include street and air transportation networks. Derrible and Kennedy characterised 33 metro systems in terms of state, form and structure. Chan et al. [21] studied the geometrical properties of the street networks corresponding to twenty German cities. Porta et al. [18] showed that one-square mile samples of urban street patterns exhibited scale-free and small-world properties. Jiang [28] and Ferber et al. [29] also drew similar conclusions in a study of 40 US city street networks and 14 city public transportation networks respectively. In a related study Jiang and Claramunt [14] demonstrated that the street networks of three cities in Sweden, Germany and USA exhibited small-world properties but not scale-free properties. Lammer et al. [19] analysed the street networks of the twenty largest German cities by considering travel time as opposed to distance. Buhl [30] studied street networks in terms of global efficiency, robustness and cost. Masucci [20] analysed the street network of London by comparing it to three models. Heinzle et al. [31], and Xie and Levinson [15] proposed methods for identifying specific spatial patterns, such as ring or star like, in street networks. There exist a number of works which analysis the current state of transportation network representations in OSM. Costa et al. [32] studied the accessibility of transportation networks in London and Paris; the data used in this study was taken from OSM. Haklay [9], Girres and Touya [33] examined the quality of OSM transportation network representations by comparison to ground-truth data obtained from the corresponding official mapping agency.

Secondly many authors have performed studies which analyse the evolution of transportation networks. Strano et al. [34] showed that the evolution of an urban street network located in an area north of Milan Italy was governed by two processes of *denification* and *exploration*. Erath et al. [23] investigated the development of the Swiss street and rail network during the years 1950–2000. Many models of transportation network evolution have been proposed. Xie and Levinson [16] proposed a model of surface transportation network evolution. The authors validated their model by demonstrating it exhibits similar characteristics to the evolution of the Indiana interurban network. Barthelemy and Flammini [35] proposed a model of street network evolution and showed that the statistical properties of this model are in agreement with empirical data. Ferber et al. [29] developed a model of public transportation network evolution and also validated this model. Levison [36] studied the relationship between street network structure and city size. Derrible and Kennedy [13] analysed 33 metro systems and specifically looked at the impact of network size. Crucitti et al. [37] proposed a method which may be used to determine if a city's street network evolution was planned or self-organised. Few studies have analysed the evolutionary process transportation network representations in OSM undergo. The work of Neis et al. [38] examined the evolution of only basic metric and topological characteristics using total street length and number of topological errors respectively. Keßler et al. [39] analysed the evolutionary properties of edit types, such as "Add Tag" or "Change Geometry", which are applied to objects. The lack of research in this area can be partly attributed to the fact that, unlike obtaining the current version of the OSM database which can be downloaded from services such as GeoFabrik [40], obtaining historical versions of the OSM database represents a significant challenge [41].

The remainder of this paper is structured as follows. Section 2 describes the geographical regions studied in this work and the network construction process. Section 3 presents analysis regarding the evolution of street networks in OSM in terms of metric and topological characteristics. Finally in Sect. 4 we draw conclusions and present some possible future research directions.

2 Study areas and network construction

This section is divided into two parts. Section 2.1 details the geographical areas studied in this work. Section 2.2 discusses the process of extracting historical versions of the OSM database and construction of the corresponding transportation networks.

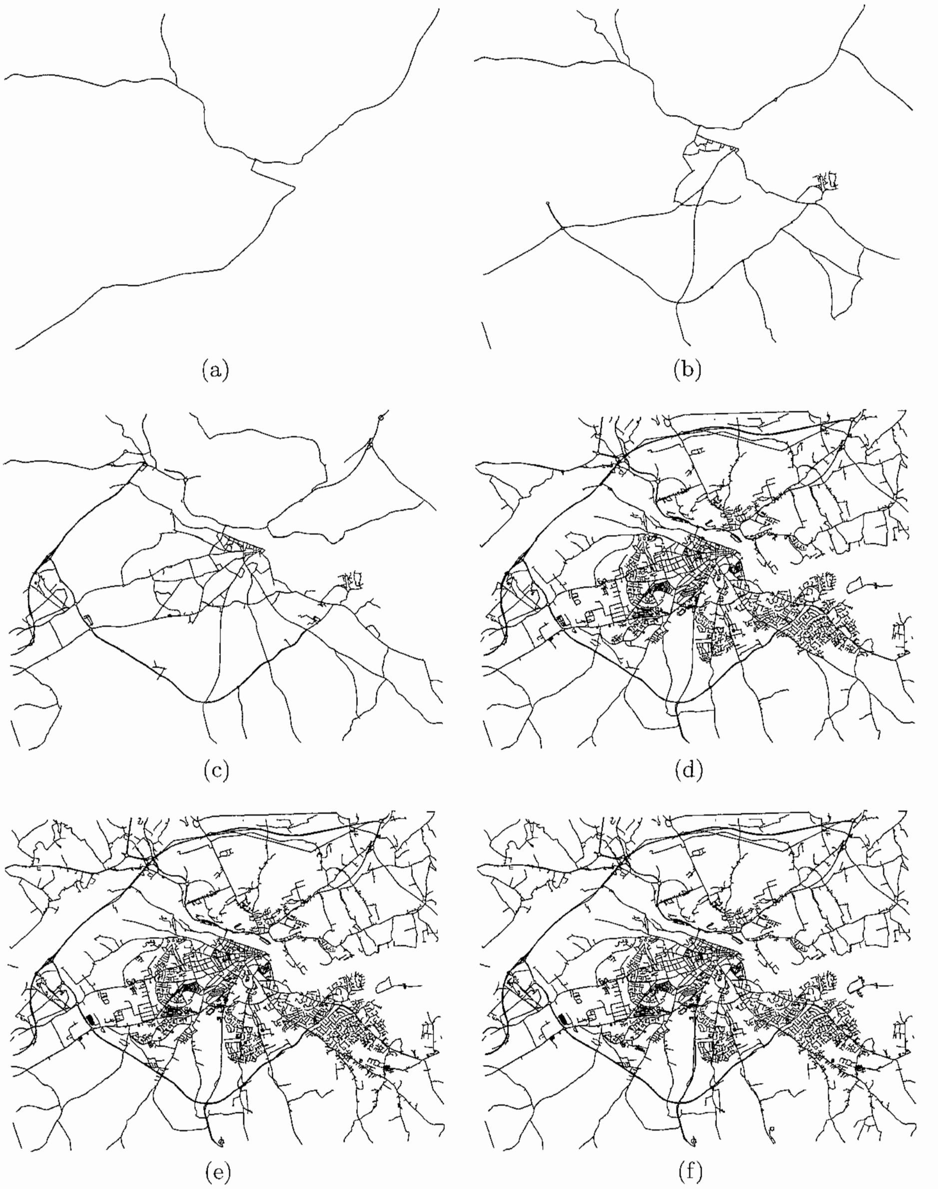
2.1 Geographical areas

In this study we analysed the evolution of OSM street network representations in the three urban regions of Maynooth, Waterford and Wicklow. Maynooth is a University town in Ireland located 24 kilometers (km) west of Dublin and has a population of over 11,000. The area of this region is $10.5\,\mathrm{km}^2$. Waterford is city located in the South-East of Ireland at the head of Waterford Harbour and has a population of over 50,000. The area of this region is $99.3\,\mathrm{km}^2$. Finally Wexford is town located near the South-East corner of Ireland and has a population of over 9,000. The area of this region is $33.8\,\mathrm{km}^2$. None of the three chosen study regions were subject to bulk data imports. Previous studies have examined much larger street networks such as London [20]. In this study we focused on smaller urban areas due to the large number of historical network versions which required processing.

For each study region we extracted the street network corresponding to the first day of each month contained in the study period 01-11-2007 to 01-10-2011 inclusive. This corresponds to a total of 48 street network versions for each region. This

Fig. 1. OSM representation of the Maynooth street network on the dates 01-11-07, 01-08-08, 01-05-09, 01-03-10, 01-12-10 and 01-10-11 are displayed in (a), (b), (c), (d), (e) and (f) respectively.

period was chosen because for each region studied it corresponded to an evolution of the network in question from containing little or no street network detail to a highly detailed street network. To illustrate the evolutionary process the OSM street networks in Maynooth and Waterford underwent consider Fig. 1 and Fig. 2 respectively which display the state of the corresponding networks on six dates in the study period.



(a) (b) (c) (d) (e) (f)

Fig. 2. OSM representation of the Waterford street network on the dates 01-11-07, 01-08-08, 01-05-09, 01-03-10, 01-12-10 and 01-10-11 are displayed in (a), (b), (c), (d), (e) and (f) respectively.

2.2 Network construction

The OSM database contains points, lines and polygons which are referred to as nodes, ways and areas respectively in OSM terminology. OSM points consist of a pair of latitude and longitude coordinates, additional information in the form of tags and a unique identifier (ID). OSM lines consist of a sequence of OSM points, additional information in the form of tags and a unique identifier (ID). Streets in OSM are

Table 1. Basic properties for each of the study areas.

Property/Date	01-11-07	01-08-08	01-05-09	01-03-10	01-12-10	01-10-11
Maynooth $\|N\|$	22	48	1018	1814	1938	2014
Waterford $\|N\|$	10	123	427	2680	3122	3234
Wexford $\|N\|$	26	30	103	692	718	2605
Maynooth $\|V\|$	25	70	1669	3116	3325	3438
Waterford $\|V\|$	13	210	751	4777	5729	5934
Wexford $\|V\|$	31	36	174	1229	1265	4410
Maynooth $\|E\|$	27	93	2138	4445	4786	4968
Waterford $\|E\|$	13	305	1219	6050	7399	7814
Wexford $\|E\|$	35	42	251	1589	1641	5425

represented using lines. OSM polygons are identical to OSM lines except that they enclose an area. Tags correspond to (key = value) pairs and commonly contain semantic information which allows us to distinguish streets from other lines such as rivers. For a given region historical versions of the OSM street network representation were extracted using the methodology described in [41]. Let N be the set of OSM lines corresponding to streets for a given region and date. The first three rows in Table 1 specify the cardinality of N corresponding to the study regions for six dates in the study period.

In order to study the evolution of the OSM street networks we converted them to a graph representation. Graph theory provides a natural environment to study street networks. A graph $G = (V, E)$ consists of a set of vertices V and edges E which represent relations between between vertices. If we assume that the vertices are the street intersections and the extremes of dead end streets, and the edges the street fragments connecting these vertices, we obtain a *primary representation* of the street network. On the other hand, if we assume the vertices are streets and two vertices are connected whenever the streets they represent intersect, we obtain a *dual representation* of the street network [20]. Constructing a dual-representation is closely related to the problem of detecting network *strokes* [42]. It was noted by Crucitti et al. [37] that a *dual representation* corresponds to an abandonment of metric distance; a street is a single node irrespective of its length. In this study we were interested in examining metric characteristics of OSM street network representations and therefore a *primary representation* was used. It is determined that two streets intersect if their corresponding OSM line representations share a common OSM point. For example consider the scene in Fig. 3 which contains two lines represented by solid and dashed lines. The dashed line contains the OSM points with ID's 1, 2, 3 and 4 while the solid contains the OSM points with ID's 5, 3, 6 and 7. Both lines share the OSM point with ID 3 and therefore intersect at this point. Following graph construction no efforts are made to improve its quality through means such as merging spatially close graph vertices [33]. The last six rows in Table 1 specify the cardinality of V and E corresponding to the study regions for six dates in the study period. It is evident from this table that the size of the network corresponding to each study region grows significantly during the study period.

3 Evolution characterisation

In this section we present an analyse of the evolution of OSM street network representations corresponding to the three study areas describe in Sect. 2.1. Through this analysis we provide new insights into the dynamics of mapping in OSM. This section is divided into three parts. Section 3.1 presents an analysis of contributor activity.

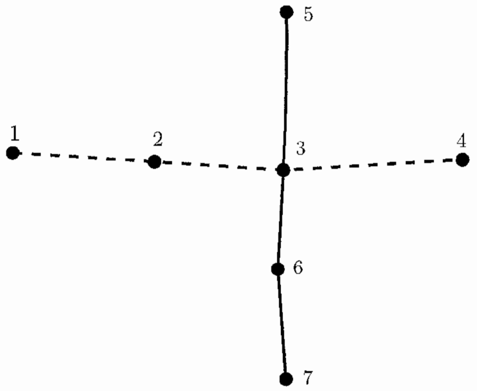
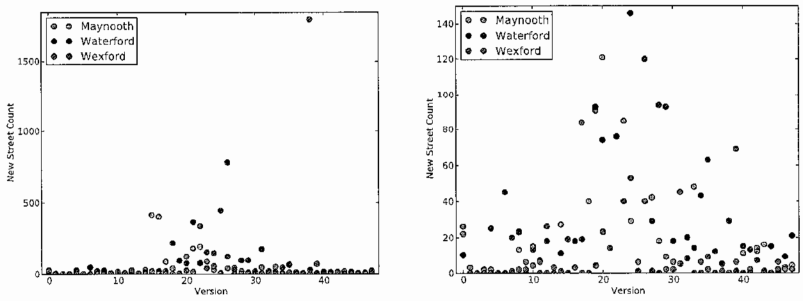


Fig. 3. The two OSM lines share a common OSM point.



(a) (b)

Fig. 4. The number of new streets added to each version of the three networks is displayed.

In Sect. 3.2 we examine metric characteristics of the evolution where the metric in question is Euclidean distance on the surface of the earth. These characteristics are a direct consequence of the fact that OSM street networks are spatial embedded. In Sect. 3.3 we examine topological characteristics. These characteristics are not a direct consequence of the networks spatial embedding.

3.1 Contributor activity

The first characteristic we examined was the number of streets added to each version of the street networks in question. That is, the growth of the variable N which was defined in Sect. 2.2. This quantifies the magnitude of contributor activity and in turn the growth rate of the network over time. Although contributor activity has previously been studied by Neis et al. [38], we examine it here with the goal of later identifying correlations with other characteristics. Each street corresponds to an OSM line and has a unique ID. Therefore the number of new streets added to a given version of the network can be determined by counting the number of new ID's which appear in that version when compared to the corresponding previous version. Fig. 4(a) displays the number of new streets added to each network version for the three study areas. Fig. 4(b) is equivalent to Fig. 4(a) but the width of the y-axis has been reduced to facilitate a clear examination of less extreme values. The mean number of streets added to each network version for the Maynooth, Waterford and Wexford regions were 44, 67 and 54 respectively. For the Maynooth, Waterford

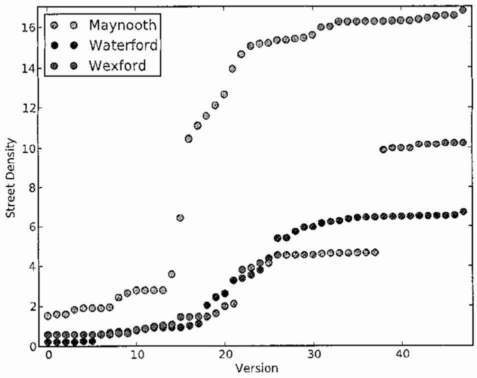


Fig. 5. The evolution of SD for each of the study areas.

and Wexford regions the maximum number of streets added to a network version were 192, 782 and 1799 respectively while the minimum in each case was 0. It is evident from the above figures that there exists significant variability both between regions and between versions of a given region. This suggests that contributes behave differently in different regions. Such non-uniform behaviour is not unexpected given that Mooney and Corcoran [6] previously demonstrated contributor tagging of objects in OSM to be very unpredictable. However in each region the number of streets added to each network version starts with low numbers before rising and subsequently falling again. This suggests that the behaviour of contributors in each region may share some similarities.

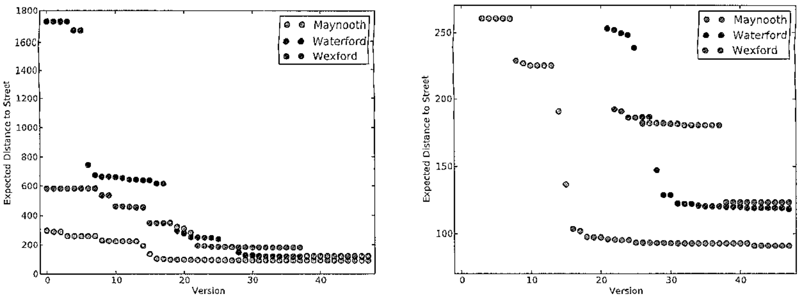
3.2 Metric characteristics

The first metric characteristic of OSM street network evolution we examined was street density (SD). This characteristic is defined in Eq. (1) where L represents the total street network length (measured in km) and A represents the size of the area (measured in km^2) within which the network is embedded.

$$SD = \frac{L}{A}\cdot \tag{1}$$

Street density has previously been used by Parthasarathi and Levinson [43] to successfully capture variations in network structure. The authors state that this characteristic may be considered a measure of the network intensity. The evolution of SD for each of the three study regions is displayed in Fig. 5. For each region this evolution is different but each broadly follows an 'S-shaped' growth in density. The process underlying the formation of this pattern may possibly be a consequence of greater contributor activity in the middle of the study period as described in Sect. 3.1. It may also be a consequence of contributors initially mapping streets predominantly of a greater length before subsequently mapping streets predominantly of a shorter length. This theory is supported by an examination of the evolution of the study areas represented in Fig. 1 and Fig. 2.

The second metric characteristic of OSM street network evolution we examined was a measure of spatial coverage which we define as the degree to which the network covers the area within which it is embedded. In order to characterise spatial coverage we propose a novel function entitled SC which was inspired by a related function of Eastaugh and Molina [44] and the study of Riitters and Wickham [45].



(a) (b)

Fig. 6. The evolution of SC for each of the study areas.

Let D be a random variable representing the Euclidean distance (measured in km) from a random point in a given study area to the nearest street in the corresponding street network. The SC characteristic is defined in Eq. (2) where E is the expectation operator.

$$SC = E[D]. \tag{2}$$

Computing an exact value for SC represents a complex problem for which we do not have a closed form solution. To overcome this difficulty we approximate SC using the following approach. A set of 5, 000 random points in the study area are selected uniformly. The straight line distance from each of these points to the nearest street is then computed. Finally the mean of these distances is determined to give an estimate of SC. The evolution of this characteristic corresponding to each of the three study areas is displayed in Fig. 6(a). A subset of this data is displayed in Fig. 6(b) with a reduced y-axis width to allow closer examination.

The evolution of SC did not exhibit any uniform pattern across regions. This non-uniform behaviour may be an artifact of possible differences in the corresponding rural urban area ratio for each region; one would expect a positive correlation between spatial coverage and the rural urban area ratio. However on a broad scale in all regions spatial coverage decreases at a slow rate initially followed by rapid rate of decrease before finally decreasing at a slow rate again. The process underlying the formation of this pattern may possibly be a consequence of greater contributor activity in the middle of the study period. It may also be a result of contributors initially mapping streets predominantly of a greater length before subsequently mapping streets predominantly of a shorter length as discussed previously.

The final metric characteristic we examined is a measure of radial density which may be defined as a measure of street network evolution with respect to the corresponding urban centre. The proposed measure is related to that proposed by Masucci et al. [20] who analysed the number of street intersections in London with respect to distance to the city centre. Masucci et al. showed that there exists a greater density of street intersections closer to the centre of London. The motivation for using a measure of radial density when analysing OSM street network evolution was to determine if similar urban centre influences exist in the mapping process.

In order to characterise radial density we propose a function entitled RD which we now define. Let $P = p_1, p_2, \dots, p_m$ be the set of m point locations (specified in km) which correspond to the set of OSM points representing streets in a given network representation. Let c be the location of the corresponding urban centre (specified in km) which was identified using prior knowledge. The radial density (RD) characteristic is

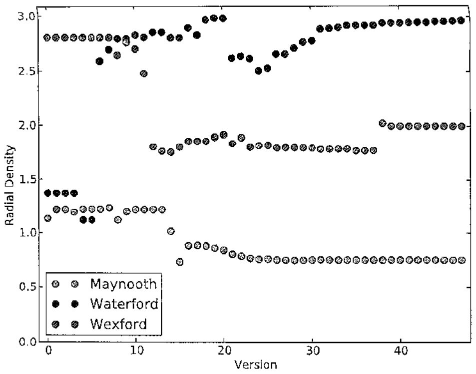


Fig. 7. The evolution of RD for each of the study areas.

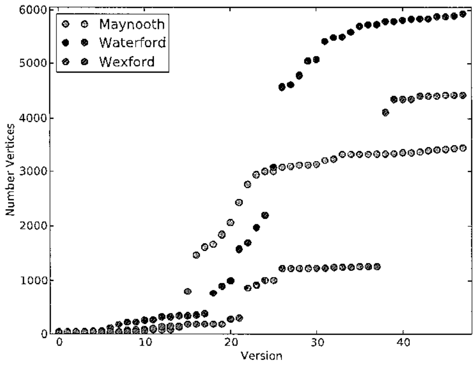


Fig. 8. The evolution of $|V|$ for each of the study areas.

defined in Eq. (3).

$$RD = \frac{\sum_{i=1}^{m} \|c - p_i\|}{m}. \tag{3}$$

The evolution of RD for each of the three study areas is displayed in Fig. 7. It is evident from this figure that the evolution of this characteristic in each of the three regions exhibits a very different pattern. In the case of the Maynooth and Wexford regions the corresponding values decrease over time while in the case of the Waterford the corresponding values increase over time. This suggests that contributors do not universally map urban centres with greatest urgency.

3.3 Topological characteristics

In this section we present an analysis of the evolution of OSM street network representations in terms of topological characteristics. These characteristics are not directly a function of the networks corresponding spatial embedding. The first set of topological characteristics we examined were the number of network vertices and edges. Both these characteristic are commonly used to describe basic properties of street network topology [28,46]. The values of these characteristics corresponding to the evolution of each region are displayed in Fig. 8 and Fig. 9 respectively. It is evident that the corresponding values for these characteristics are highly correlated. It has been previously demonstrated that many characteristics of real world networks tend

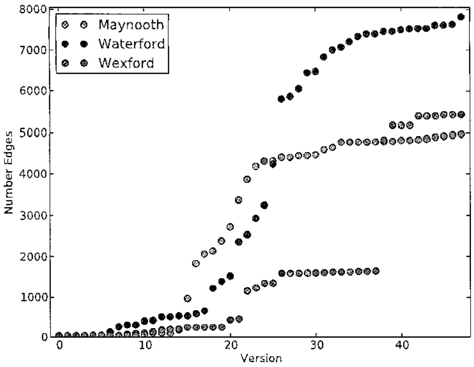


Fig. 9. The evolution of $|E|$ for each of the study areas.

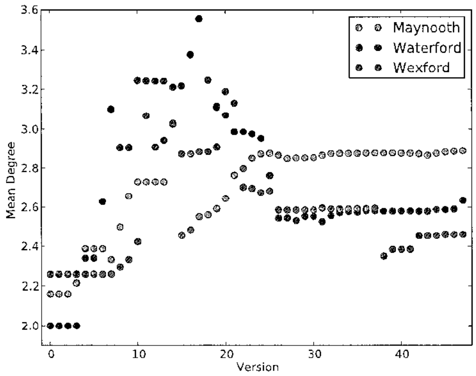


Fig. 10. The evolution of mean vertex degree for each of the study areas.

to be correlated [47]. The evolution of both characteristics do not exhibit any uniform pattern across regions. This non-uniform behaviour may be an artifact of differences in the areas of the three regions studied; a larger urban area will naturally have a greater number of network vertices and edges. On a broad scale the evolution of both characteristics in all regions follow an "S-shaped" growth. The process underlying the formation of this pattern may possibly be a consequence of greater contributor activity in the middle of the study period.

The next topological characteristic we examined was the mean vertex degree. Comparing the corresponding complete degree distributions is a common tool when comparing the topology of two networks [27]. However in this study our goal was to compare the topology of 48 networks in each of the study areas. We therefore choose to use a summary statistic of the corresponding degree distributions, in this case the means, to allow a meaningful comparison. Also Barthelemy [27] states that in the case of streets networks, and more generally planar networks, the degree distribution is not a suitable approach to characterisation and is of "little interest". Chan et al. [21] successfully used mean vertex degree to characterise the topology of street networks. The evolution of mean vertex degree for each of the three regions is displayed in Fig. 10. It is evident that no pattern, even on a broad scale, is common to all regions. For the Waterford region the evolution followed a pattern which starts with low values before rising and subsequently falling again. On the other hand, for the Maynooth and Wexford regions the evolution followed a pattern which starts with low values before rising, then falling and subsequently rising again.

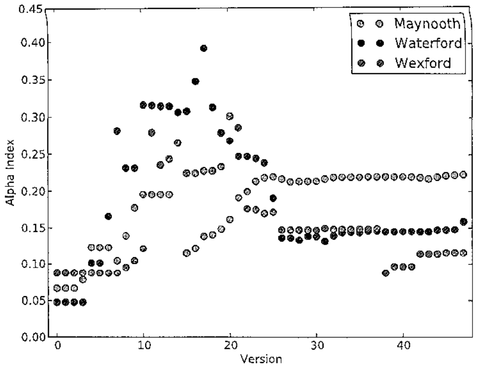


Fig. 11. The evolution of α for each of the study areas.

The final topological characteristic we examined was the alpha index (α) which is defined in Eq. (4). The alpha index measures the number of cycles in the network and in turn is a measure of network connectivity [36]. It takes values in the interval $[0, 1]$ where a value of 0 corresponds to a network with no circuits while a value of 1 corresponds to a completely interconnected network. As noted by Xie and Levinson [15] the use of this index is limited with respect to its ability to describe the structure of the underlying network. Therefore the authors proposed algorithms to identify specific structural patterns, such as ring or hub-and-spoke, in street networks. However in this work we are not interested in understanding the exact structure of the street network in question but instead the process by which it was mapped by OSM contributors. This was the motivation for using the alpha index. The evolution of this characteristic for each of the three regions studied is displayed in Fig. 11. The pattern exhibited by the evolution of this characteristic appears to be highly correlated with that of the mean vertex degree represented in Fig. 10. This suggests that the underlying process which results in its formation is also the same. However it is unclear what this process is.

$$\alpha = \frac{|E| - |V| + 1}{2|V| - 5}. \tag{4}$$

4 Conclusions

This paper presents an analysis of the evolution of street network representations in OSM which is a form of VGI. The analysis focused on the evolution in three urban areas in Ireland. Due to the fact that street networks are spatially embedded we characterised the evolution of these networks in terms of metric and topological characteristics.

In the case of all characteristics examined no uniform behaviour was exhibited across regions. This suggests that contributes behave differently in different regions. However some characteristics, such as street density and spatial coverage, exhibited broadly similar behaviour across regions. This may be a consequence of similarities in the degree of contributor activity. However this also suggests that contributors may conform to some intrinsic universal mapping procedures. For example analysis of street density and coverage suggests that contributors initially map streets predominantly of a greater length before subsequently mapping streets predominantly of a shorter length. On the other hand some characteristics, such as radial density, exhibited contrasting patterns in different regions which could not be easily explained. This lack of uniform behaviour may be attributed to the fact that contributors are not subject to central coordination or explicitly specified mapping procedures.

This paper represents a potential starting point for many possible future research directions. Some possible directions include the following. Firstly it is possible to analyse the evolution of semantic or tag characteristics corresponding to OSM street networks. Also since one can determine the contributor responsible for each individual edit to the OSM database it is be possible to analyse contributor activity with respect to street network evolution in greater detail. Finally it is be possible to analysis street network evolution with respect to convergence to ground truth data. Such work could potentially provide an unsupervised means to make statements regarding data quality.

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