Venezia the Living City

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Abstract. What makes some cities successful and others less so? We propose here that the structure of a city and the way it enables motion through its streets; i.e. its walkabilty, predicts its usability. We further suggest that this can be seen by studying the network structure of a city's streets, since the network reflects the history of their use. As an example of our claim we will study Venice. The city is a good example for our hypothesis as it is both universally walkable and one of the most purposefully sustained cities in existence. To study the network of Venice in a way that reflects the need to adapt it to the motion of people we will single out those elements of the city that are most changeable, that is, those that can be easily added or created by eliminating some barrier. We will study the bridges between islands (*ponti*) and contrast them with the intra island streets (*calli*) that make up most of the pedestrian network of Venice. Even in its uniqueness, looking at Venice will help us develop a methodology for analyzing the current state of a city graph and gather some insights on how it achieves its purpose through historical analysis of its evolution.

Keywords: Social network analysis · Complex networks · City design · Venice · Complex network evolution · Urban networks · Betweenness centrality · Complex systems · Adaptation

1 Introduction

We propose here a study of cities as living systems. Living systems are always in flux, *panta rei* – everything flows. Much like one can never steps into the same river twice, since the essence of the river is the shifting waters that flow in it. Cities are also made of their moving parts. The streets and neighborhoods, as static as they may seem, are like riverbeds, embodiments of the flows they contain. Cities are constantly being rebuilt, they grow and change and adapt but still retain something of their character.

No city better exemplifies this trait than Venice. The city that has been sinking into the lagoon since its inception and yet appears unchanged. What is

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the secret of Venice's resilience? Can it be learned by studying the networks on which things flow in Venice? Venice is a medieval city that still functions today in pretty much the same form. Like all cities of its time, and to the extent it can be considered "designed", it was designed for the scale of humans and donkeys [17].

In the 15th century Venice had an advantage over other cities because of its canals. These canals and their uses to transport goods and people at high volume, only came to other cities with the invention of subways and trams. However, in other cities acquiring the capabilities of mass transport came at the price of creating urban sprawl and effectively changing the scale of cities from that of man and walking to that of the car. Not so in Venice where outside the canals it is still the most walkable of cities. In Paris, London, New York and Rome urban planners are trying to create modern walkable sustainable city centers. It appears quite clear that if we wish for our city centers to thrive this is what we need: A return to human scale. The idea of walkability is also at the heart of futuristic projects such as NEOM, also known as the Line - the planned city concept of the crown prince of Saudi Arabia, and in the critical response to the Line, which suggested that a more human scale possibility for a futuristic walkable city would be a circular design [18].

We would propose that Venezia, the medieval city, can teach us how to create viable walkable neighborhoods with mixed usage and mixed demographic communities [5]. To start our research we will look at the network structure of the paths of Venice, including all the bridges, to identify their scale(s) and patterns of connectivity and in that way suggest what could be the best design principles for creating viable walkable cities. We would like to connect the network structures of paths to the way people traverse these paths; to do so we will look at the role of the most changeable components of the Venetian pedestrian networks: The bridges (ponti).

Helpfully, the routes of Venice all receive different names, which are related to their history and function [22]. Many of them are called *calle*[1] and connected across canals by *ponti*[2] (bridges). These last elements are much more easily constructed and removed. We therefore hypothesize that when they are added they represent a selective change to the networks and their connectivity. Indeed, as we will show below, when we consider bridges separately we find that their betweenness distribution has a higher value than the rest of the network and that two stretches of bridges with the highest betweenness may reflect how Venice evolved from a centralized mercantile center to more distributed place to live in, be visited and explored.

To test our hypothesis that the city has adapted and that the main loci of adaptation are the bridges we analyzed the graph representation of the urban structure of the city of Venice trying to answer the following questions:

[1] In Italy, the most common name for a street is *strada*; Venice is unique in the way it calls its different ways: *calli* (street) or *campo* (squares).

[2] Please note that we will be using the Italian (and sometimes Venetian) convention for plurals throughout this paper.

- What is the large-scale structure of connections in the city? Are different types of ways providing connectivity in an interchangeable way or not? Specifically do the *ponti* (bridges) between islands represent a specific class of connectivity in the network?
- Does the connectivity provided by the edges reflect the adaptability of the city structure in some way? Can we identify key edges that describe how Venice is connected right now and suggest how it is changed over time?

The rest of the paper is organized as follows: Next we will present the state of the art in studying cities from the point of view of its network structure; Sect. 3 will introduce the dataset used for the study and how it has been obtained and processed. Results will be presented in Sect. 4; we will finally discuss them and show our conclusions in Sect. 5.

2 State of the Art

Our study aims to combine understanding from several existing points of view of city design and network analysis. This is a preliminary study on which we hope to first develop a algorithmic methodology and then build a more comprehensive analysis incorporating all these aspects.

To understand the design of cities some have suggested that we must understand how the functions of a city combine [8] the way people move through the city [4,7] and how they observe it; that is, how the iconic parts of the city make those navigating through the city achieve a sense of place [11,19]. In many cases, in order to study each aspect a network representation of the city was made where nodes can be either specific locals connected by edges representing routes [6,19] or they may be more general aspects of the city or zones. In studying Venice, however, we are inspired by a book which created both networks of view and of motion in Venice to show how these combine in the constructed logic of the Venice in particular and as an inspiration for city design in general [20].

Once the city is transformed into a network the tools of complex network design and analysis, which have been also used to study other complex living/changing networks, can be applied [8,14], to measuring the underlying network of Venice. We will apply different levels and types of centrality to study different parts of the city's underlying network [3,4,21] and the way it divides into communities or neighborhoods (in the network analysis sense [15,23]).

Of especial interest to us are those attempts at studying the network not as a static map but as a substrate for motion and changes in connectivity as the dynamics of interaction between components of the system emerge. Such methods have been used before to study protein interaction networks [10] and social network interactions [9] but are equally applicable to the study of motion and interactions in a city [12]. Thus one could use methods of community identification based strictly on the structure of the network [15] or on the motion of agents on the network with differing levels of memory related to past choices on motion [23]. Taking this later approach or other simpler choices to identify types of nodes by their structural stability should improve on other analyses that did not consider that the networks we are studying, even if they describe something of apparent stability like a city, represent only the template of potential interactions.

Thus, we will next use the tools of complex network analysis to understand the current urban structure of *Venezia*, and check how it is shaped by the physical constraints, the perception of the city from a personal point of view, and its evolution by the creation of new edges connecting nodal points in the city.

3 Methods

There are two sources of data that can inform about how motion occurs in Venice: We could study the motion of individuals or we can study the network of pathways. Although it would be good to combine both viewpoints, we will as a starting point, present here solely a study of the network of pedestrian pathways that connect the islands of Venice.

OpenStreetMap hosts a frequently updated information on Venice (and most cities in the world). We have used the `osmnx` Python library to download the data using the *placename* "Venezia-Murano-Burano, Veneto Italy"; data was downloaded in August 2024. The preparation of the data included these steps

- Extract, using the `graph_from_place command`, the graph for that specific place, using the `walk` network type, to exclude waterways and focus on the actual *calli* of the city. The *calli* compose a graph which, by nature of its creation, is a complex graph, and one that describes how the city of Venice and its different parts can be reached by foot. The nodes of this graph will be junctions of any two segments of footpaths, including of course squares, while edges will be these footpaths that will include all or part of the *calli*, bridges, and other street under different names. This results in more than 14K edges.
- The original graph is directed, we made it undirected by merging all edges with the same origin and destination in any direction.
- Data in the original graph file is attached to edges in the processed graph, by adding attributes that classify them as bridges (*ponti*) and color them according to their traits.
- Save as a graph to a file. This is an XML file in the GraphML format.
- The directed graph is then converted into an undirected one, choosing randomly the type of one of the two directions as the edge type.

Not all paths are of equal importance even before we know how people use them. Beyond the *calle* (street) that connects squares (*campi* and *campielli*) on a given island one needs *ponti* (bridges) to move between islands. Identifying where bridges are and how they impact the scale and connectivity of the network can also give us an indication of places where the networks changed. While changing the pathways of a *calle* requires the creation or destruction of buildings, a simple bridge will connect two existing islands and can be quite crooked[3] to accommodate existing paths on both sides.

[3] There are the so called *ponti storti*, literally crooked bridges.

Even as all these edges are walkable, OSM makes distinctions among them; these different types ("pedestrian", "footway" or "service") have been eventually found irrelevant for the current study, except it can have additional information such as classifying segments in a bridge as "steps"; this is mainly due to the fact that most edges in the graph are forbidden to vehicles so distinctions between different types are really lost. We have, however, left these distinctions in the dataset so they can be used for future studies with a different focus.

Besides bridges, another type of walkway in Venice, which is more easily added or removed is the *sotoportego*, (literally - under the gate) which can be an underpass or, in many cases, simply a open passageway; tourists tend to avoid them, but locals use them extensively for their navigation of the city. Together with bridges, they are a very common feature of any kind of itinerary in Venice. While 6.94% of all edges are bridges, 7.49% are classified by OSM as *tunnels*, which is the closest form they have.

Personally validating the roles of edges we assigned is beyond the scope of this study. However, the open source process at the heart of OpenStreetMap guarantees that eventually any errors will be corrected by local users.

The processed dataset that is used in this paper will also be made available as open data in a GitHub repository.

4 Results

The network measurement we are going to work with is edge betweenness, a concept introduced by Newman and Girvan [15] in the context of their proposed community detection algorithms; in general, it represents how important a specific edge is within the network, that is, how many paths from a random part of the network to another would pass through it. It is related to community structure in the sense that, by cutting those links, we would reveal the existence of those communities; of course, it could also be related to the amount of traffic that every edge would need to handle. But from our point of view, it is more interesting to interpret high edge betweenness as a semi-autonomous decision that tries to (in many cases literally) bridge structural gaps so that newly linked communities can be reached, or can be reached faster. That is why it is interesting to look at the bridges' betweenness and their rank.

The edges with the highest betweenness are listed in Table 1. We use the same name of the edge as shown in OpenStreetMap, which sometimes includes two or even more elements. For instance, the first one, `['Ponte del Sepolcro','Riva degli Schiavoni']`, could have a composite name with *Ponte* (or bridge), and *Riva*, which is essentially a promenade by the edge of one of the big *canali*[4] or by the *Bacino di San Marco*, or "San Marco pool", the big expanse of the lagoon between San Marco and the Lido.

The two groups of edges with the highest betweenness are represented in Fig. 1. It should be noted that all those edges are *contiguous*, so even if they

[4] Please remember that there are only 3 "*canali*" in Venice: Canareggio, the Gran Canal and the Canal della Giudeca; the rest are called *rii* or rivers.

Table 1. Top edges, ranked by betweenness, showing the name of the edge and its type

Edge name	Betweenness	Bridge?
['Ponte del Sepolcro', 'Riva degli Schiavoni']	3812670	TRUE
Riva degli Schiavoni	3768968	FALSE
Riva degli Schiavoni	3670990	FALSE
["Ponte de la Ca' di Dio", 'Riva degli Schiavoni', "Riva de Ca' di Dio"]	3642880	TRUE
Riva degli Schiavoni	3621503	FALSE
Riva de Ca' di Dio	3584368	FALSE
Riva de Ca' di Dio	3568553	FALSE
['Riva San Biasio', "Riva de Ca' di Dio", 'Ponte San Biasio delle Catene']	3552743	TRUE
Riva degli Schiavoni	3552725	FALSE
['Riva degli Schiavoni', 'Ponte de la Pietà']	3535148	TRUE
Riva degli Schiavoni	3528388	FALSE
["Ponte dell'Accademia", 'Campiello San Vidal']	3053339	TRUE
Campo Santo Stefano	2995551	FALSE
Campo Santo Stefano	2989780	FALSE
Riva San Biasio	2988618	FALSE

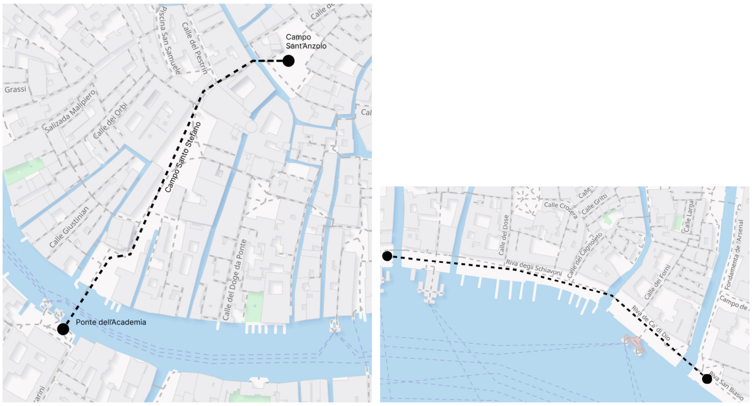

Fig. 1. Figure based on annotated screen capture from OpenStreetMap. Black broken line represents edges with the highest betweenness (from the first to the eleventh in Table 1, right, the next cluster of edges, left).

appear as different edges, they are a continuous path that goes from the *Ponte de la Pietà*, through what is one of the most important nodes in the water transportation network, the San Zaccaria vaporetto stop, to right after the *rio del Arsenale*. The Ponte del Sepolcro, with the highest betweenness, is at the left hand side, close to the western end of this path. Besides the fact that the edge with the highest betweenness is a bridge, and 4 of the top-10 are also bridges, another fact that draws our attention is the closeness (but not identification) to the main hub in the city, San Marco, but also the fact that they are all bordering the water, being literally part of the interface between the water transportation system and the on-foot pathways, even if the water edges were not taken into account. This points to an *organic* nature of the growth of the network.

The second block with the highest betweenness goes from the Campo Sant'Anzolo through Campo S. Stefano to the Ponte dell'Accademia[5], also shown in Fig. 1, left. It is not, in this case, bordering a *canal* or a water basin, but going through several *campi* (or squares) ending up in one of four bridges that crosses the Grand Canal[6]. Again, we find three bridges in this path. All in all, 9 bridges are in the top 29 by edge betweenness, that is, 31%, which is beyond the 6.94% that is the actual percentage of edges that qualify as bridges.

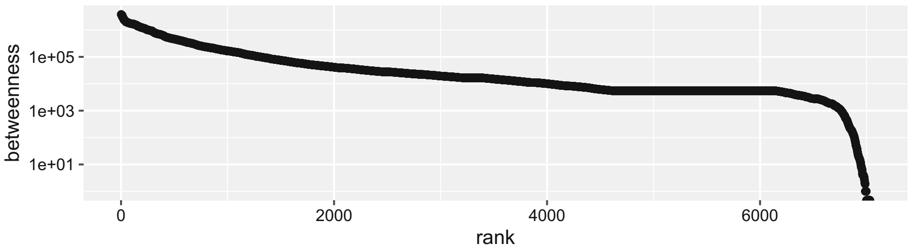

Fig. 2. Rank-value plot of edge betweenness

We can get another indication of this by making a log-rank plot of edge betweenness, shown in Fig. 2. This scale shows the well-known broken-stick model, with a slowly descending slope up to a certain point; it goes flat for a few thousand edges and then decreases very fast.

We can look at this from another point of view, shown in Fig. 3, an histogram of edge betweenness values, showing an uneven distribution, where the most abundant value is somewhere around 1000 and 10000, namely, 5519. This number which represents the size (number of nodes) of the Venice network and corresponds to the plateau in the chart in 2. A sampling of the edges included in this set reveals that they are mainly *rami* and *corti*, that is, blind alleys and little squares connected by another alley to a bigger street or *calle*. Along with bridges, another major feature of Venice is that it is limited on all sides by the lagoon. Thus alongside the connections of bridges we had a plenitude of dead ends away from the main thoroughfares. This skews the distribution, but also tells you a lot about the *organic* way this street network was grown to create what is literally a closed fully connected network.

Figure 4 is a violin plot of edge betweenness for bridges and the rest of the edges excluded bridges, which shows that, on average, edge betweenness is much

[5] Except for Riva San Biasio, which is actually contiguous to the previous segment.

[6] Ponte dell'Accademia, Rialto, the Ponte della Costituzione and the *Ponte degli Scalzi* have been built over the Grand Canal.

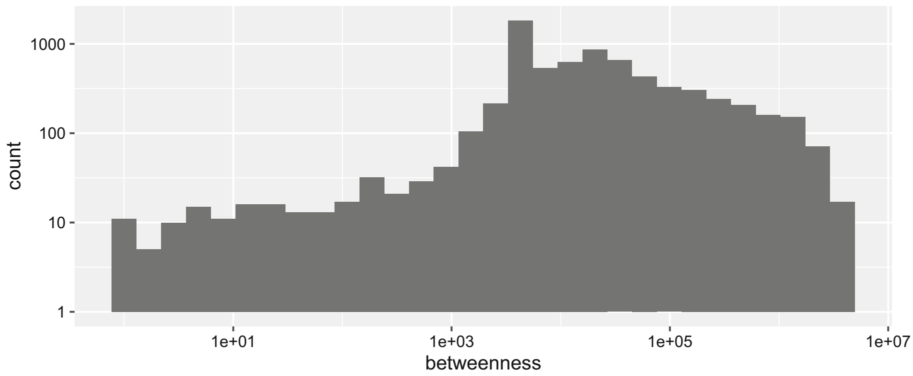

Fig. 3. Log-log histogram of edge betweenness value

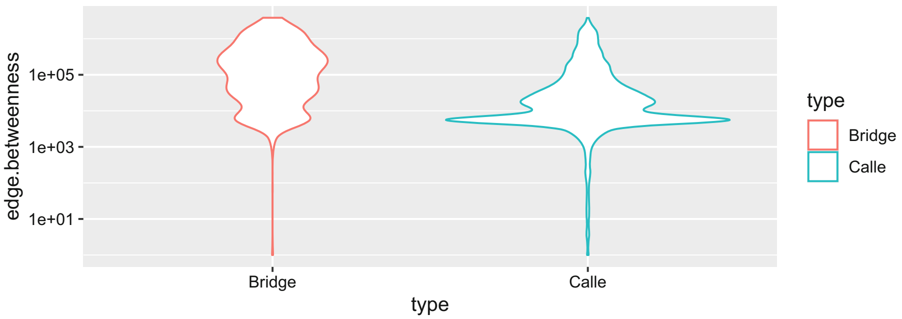

Fig. 4. Boxplot of edge betweenness for bridges and calli

higher for the former, and that *calli* or streets do have lots of outliers. The significant difference highlights the fact that bridges have been created in places where a structural gap was perceived, so that they complete the graph in such a way that there are few street (or street segments) that can complete with them, individually or on average.

The median of edge betweenness for bridges is 1.1542023×10^5 and the rest, which we will generically call *calli*, has 1.3057351×10^4 has median edge betweenness. Since as we have seen in Fig. 4 the values are not centrally distributed, we have considered the median a better central measure than the average. The difference between medians is significant, median for bridges being 9 times as high as for *calli*. This comparison highlights the fact that bridges are significantly better connectors than the rest of the streets.

Although blind alleys are an important feature in the Venetian urban fabric, its prevalence might obscure larger-scale measures related to way people moves around in the city; in most social networks, anyway, nodes with degree 1 are usually dropped; we therefore next eliminated nodes with a single degree (dead ends) and examined the resulting network.

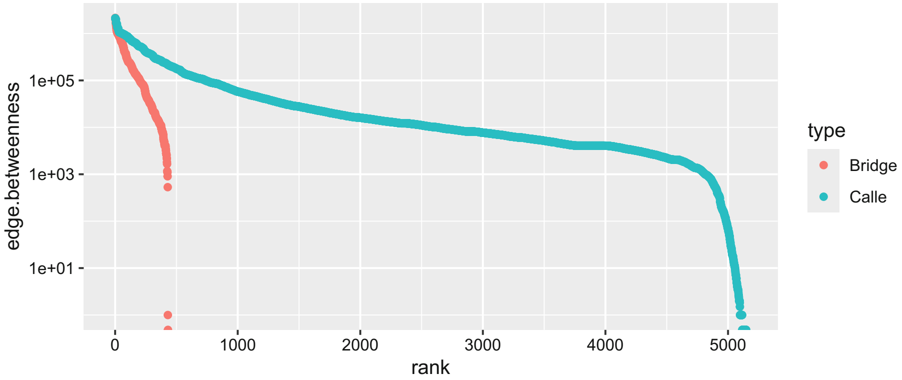

Fig. 5. Log-rank plot differentiated by type of path

After pruning *leaves*, we made an edge-betweenness log-rank plot for bridges and the rest of the edges in Fig. 5. The plateau that we saw in Fig. 2 has disappeared in both, although there is a small plateau left in the case of *calli*, probably due to the creation of "new" leaves. The position of the plateau is the same, at the transition between the power law and the descending step. The bridges, however, show a very steep power law (with some outliers), highlighting the fact that every path within a bridge, when eliminated, will isolate a big part of the graph; after pruning, median edge betweenness for bridges is 8.6897001×10^4 and for calli 1.0325884×10^4. The median betweenness measure for bridges is still 9 times those for non-bridges, although the multiplier is slightly smaller; when dropping degree-1 nodes, many edges with a low betweenness that connected those nodes have also been dropped, and most of these were *calli*. Still, the structure shows a very solid difference between bridges and other kinds of connectors. This again answers positively research question one: even if we do not consider the blind alleys/degree-1 nodes, bridges provide much higher connectivity to different parts of the city than other types of paths; the only caveat here is that the bridges one would expect to actually be the ones with the highest connectivity, such as the Rialto, are not really on top, although they are in the top-50 s.

Even non-bridges are not an uniform class of way in Venice. Returning to the full graph, including all edges, Table 2 shows how many times specific street names appear in the graph (with those appearing less than 50 times dropped). Every segment identified in the OPEN STREET MAP has one or several street names; for consistencies sake, we have extracted the first word appearing in the first street name of each segment; for instance, `['Campo dei Gesuiti', 'Fondamenta Zen']` would be a *campo*. The first name can be assumed to be random, so this choice does not introduce any kind of bias; this is a needed simplification, however, since analyzing combinations of two types of streets would obscure the analysis of the whole structure. This obviously implies that the table above counts as any type only those segments that have that type in their single street name, or as the type of the first street name in a number of them.

Bearing that in mind, *calle* is the most common, but *fondamenta*, which border canals and the lagoon, also appear quite frequently; other denominations correspond to squares, with *campo* being a big one and *corte* a small one. While *rio* is, effectively, a canal, in this case it corresponds to *rio terà*, or buried canal, streets created by paving over canals, of which there is a good amount in Venice, most of which were created in the 19th century and onward. The name, as can be seen, represent different functions, so it would be interesting if that function is reflected in their edge betweenness.

Table 2. Types of street found in the graph (more than 50 times) and their frequency and median edge betweenness, sorted by the latter.

Segment name	Occurrences	Median betweenness
Riva	67	311963.53
Ponte	101	100846.11
Salizada	111	43713.46
Fondamenta	558	40509.26
Rio	184	32249.50
Viale	99	23355.58
Calle	1671	16551.00
Campo	448	15435.03
Piazza	59	14060.82
Campiello	96	11864.31
Piazzale	96	11009.79
	2653	9294.76
Corte	196	5519.00
Ramo	262	5519.00
Sotoportego	94	5519.00

The edge betweenness for edges with a certain name are shown in the same Table 2. We have already seen (Fig. 1 and Table 1) that the *rive*, together with the bridges that join them, are the segment with the highest betweenness. As indicated, these border the Gran Canal as well as the parts of the city that border the water. In most cases, and despite the image of Venice, there is a path with a varying width between water and the houses; as a matter of fact, *fondamente* is the other kind of thoroughfare that shares this feature. *Ponti*, on the other hand, go over water, and *rii*, which are fifth in the ranking, are paved canals, so we find that 4 out of the top 5 paths in terms of median betweenness are at the same time tangent with water and also consequence of a human intervention at a point in time that tries to avoid structural gaps by creating new edges. The city itself flows over, by the side, and around water, quite literally.

The last type of way in the top 5 in terms of betweenness, which is not related to water, (to the extent that anything in Venice can be) are *salizade*, which means *paved* (street or lane). These streets were not opened, but certainly chosen to be paved over others, that were simply open ground initially; these were [2] the main streets in every parish, paved with bricks in the 13th century. The fact they still maintain a high betweenness is witness to the self-organizing manner that has informed decisions in Venice from the beginning, but also to the way the city has evolved in such a way that most thoroughfares maintain their connective power eight centuries later.

The rest of the ranking is occupied by different kind of streets, with *viale* on top; all these are concentrated in the Castello area, most of them in a part reclaimed from the lagoon in the 1920s. The bottom of the ranking is occupied by no-name segments, *corti*, that is, closed squares, *rami* or alleys, and finally, *sotoporteghi*. These have the same median value because they are mainly dead alleys or squares with a single exit. This edge betweenness value is related to the number of nodes in the network; there is a single path that connects them to the single node at one of their ends. Median value do not fully reflect the variability and diversity of these three kinds of nodes, but further investigation is beyond the scope of this paper.

This answers our second research question: the type of ways which have the highest betweenness are those that can be added in a relatively easy way, by paving over *rii* or bridging over water *ponti* or providing a water-side platform (*fondamente*) for houses lining the water. Since these new edges close structural gaps, they immediately become high-betweenness pathways, reflecting the adaptability of the city structure and making it really a *living* city.

5 Discussion and Conclusions

All in all we answered both of our research questions about Venice, characterizing the structure of connections in the city and the special role of bridges in connecting the disparate parts of Venice into a whole. We have further shown that by contrasting the betweenness of different types of edges we can identify meaningful differences in connectivity. Finally, we identified two major connection of points of the Venice network. Interestingly these do not include the two main focus points of Medieval Venice - the Rialto and Piazza San Marco, which are still identifiable by other network analysis means [19,20]. The two foci of betweenness we identified are also not key tourist destinations. Potentially this reflects more recent changes and adaptations of Venice. The construction of the Academia bridge, connecting Dorsoduro with its many academic institutions and student dorms and the expansion of residential neighborhoods into Castello, in areas that before were the boat yards adjacent or related to the Arsenale. Areas that now encompass also the Giardini that host what is now the second key attraction of Venice from May to November, the Art and Architecture Biennale, which started in 1895. A very short while ago in the history of la Serenissima.

The distribution of edge betweenness we observed suggest a network with complex, scale free statistics that is limited by the edge constraints and size of the network [1]. Venice is not infinite: It is in-fact encapsulated by the lagoon. The dead ends and closes *campi* of each island thus influence the distribution of betweenness, indicating for us the size of the network that is Venice. However, the through network of bridges (and calle) exhibit an interconnectedness that allows for the flow and interaction of people across all scales of the city. This kind of structure is found in many places in biology where interaction of cells are important and must be condensed into local tissues; for instance in our lymph nodes, where immune responses are initiated, immune cells move more or less single file through a intricate maze of lymphatics interacting rapidly with a wide array of different cells until they meet a partner immune cell which corresponds to the same pathogenic disease, ensuring response to pathogens and lack of spurious responses to changes in the body. This kind of structure is no less important at the scale of a city, as it enhances the ability to meet people you know, and also new people you may need to know, without getting stuck in one local or limited set of interactions. Better than a line or a circle [18] to enhance human interaction one needs a friendly maze, which is exactly the kind of structure a polity like the republic of Venice needed to ensure a reasonable, and reasonably stable, government [13].

As future lines of work, it would be interesting to analyze the same graph using a *dual* representation, which swaps nodes for edges and vice versa [16]. The fact that the edges with the highest edge betweenness are in fact contiguous segments leads us to think that this approach would help us better identify unique paths that play an important role within the urban fabric. It would also be helpful to perform, to the extent that it is possible, a temporal analysis by dating all edges that can be identified and then proceeding to show how overall connectivity changes; even a simple procedure of elimination of high-betweenness edges would help in that sense, and would help us to identify the structural holes that these edges cover. Finally, as we mentioned at the start, it would be good to combine our analysis of the network of paths in Venice with the analysis of the actual patterns of motion of people on the network.

However, even if only taking into account our simple first step of analyzing the betweenness of edges of different types, we have shown here that Venice can indeed be considered a living adaptive system. Living things maintain themselves. However, this type fo stability is neither static nor the acquisition of some chemical steady state. It is not even the motion between several constant attractors or the classical idea of homeostasis, the active return to a constant state. Instead what we describe here is an emergent stability that depends on the ability to adapt and change the living system's component interactions. Venice remains Venice because of the ability of the network that constructs it to change.

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