WDN-TAILORED EDGE BETWEENNESS FOR ANALYSIS OF DISTRICT METERING AREAS PLANNING

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ABSTRACT

Many complex systems of the real world can be modeled as networks using the complex network theory (CNT). Water Distribution Networks (WDNs) are special infrastructure networks connecting vertices, named nodes, by means of edges, named pipes, which are material elements transferring water to customers. Considering the spatial characteristics of WDNs, there is the need for tailoring CNT metrics in order to analyze the domain of hydraulic equations as useful tool for analysis, planning and management tasks, before and after the hydraulic simulations. In the last decade, several researchers studied the behavior of spatial networks and more recently CNT has been used for domain analysis of WDNs. In fact, the WDN domain features drive the emerging hydraulic behavior while the application of the momentum and continuity equations and boundary conditions specifies the hydraulic status.

This work proposes and discusses the WDN-Tailored Edge Betweenness, a new CNT metric obtained starting from the classic edge betweenness and tailoring it in order to capture the domain features of the hydraulic systems. The paper applies such novel centrality metric to support planning WDN District Metering Areas (DMAs) in order to evaluate the modification in the network domain due to the districtualization (i.e. closed gates). Based on a real case study, the original WDN-Tailored Edge Betweenness and those related to various DMA solutions were compared to gain information about the vulnerability and new relevance of pipes/paths.

Keywords: Complex network theory, edge betweenness, domain features, water distribution networks, District metering areas.

1 INTRODUCTION

Today, the Complex Network Theory (CNT) allows to model the most part of the real systems as networks. The graph theory is the mathematical basis of CNT where the networks are composed of vertices, which represent the elements of the systems, and edges, that indicate the interactions among them. CNT studies biological, technological and social networks (Newman, 2010). The infrastructure networks belong to the technological ones and water distribution networks (WDNs) are special infrastructure networks belonging to the subset of spatial networks because their connectivity structure is constrained by environmental factors (Barthélemy, 2011; Giustolisi et al., 2017). The fact that their topology is limited by spatial constraints, e.g. streets and buildings, which drive their planning and construction, imposes severe limitations on network connectivity and layout, and hence WDNs needs to be studied differently from other complex networks. Several studies of CNT have focused on understanding the behavior of spatial networks (Barthélemy, 2011; 2014; 2018), such as WDNs (Giustolisi et al., 2017; 2019), and CNT tools have been already used by several researchers for studying spatial networks but without tailoring, and therefore, without the possibility to capture the specific domain features of these spatial systems. For example, Yazdani and Jeffrey (2010, 2011, 2012a, 2012b) adopted centrality metrics (Freeman, 1977; 1979) for studying WDNs robustness and vulnerability, but their results shown that the spatial constraints limit the use of these metrics and provide unreliable results. In other words, the CNT centrality metrics proved to be a useful tool for WDNs analysis, planning and management although they requires tailoring to consider the spatial limits of such systems. To this purpose, Giustolisi et al. (2019) proposed a tailoring of the most appropriate centrality metrics useful to support the WDNs studies. They stated that not all CNT centrality metrics are suitable for WDNs analysis and proposed the tailoring of the CNT centrality metrics based on the concept of shortest paths, because they characterize the behavior of spatial networks with respect to the flux of information (Borgatti, 2005); flux of information for WDNs corresponds to water flowing in the pipes. More specifically they presented and discussed the edge betweenness centrality...
(Girvan and Newman, 2002), a very informative centrality metric for analyzing the behavior of spatial systems. They tailored the classic edge betweenness and proposed the WDN-Tailored Edge Betweenness (Giustolisi et al., 2019) useful to analyze the hydraulic behavior of WDNs, i.e. to rank pipes relevance. The resulting tailored metric allows to capture and analyze the domain features of WDNs, which drive its emerging hydraulic behavior.

Starting from the WDN-Tailored Edge Betweenness (Giustolisi et al., 2019), the present work aims to evaluate the domain features of real networks before and after the planning of District Metering Areas (DMAs). In this sense, the WDN-Tailored Edge Betweenness is evaluated for the original system and, after the DMA planning, for a DMA solution. The DMA planning involves a first step of network segmentation (Giustolisi and Ridolfi, 2014), to identify the candidate locations of closed valves or flow meters, and a second step to choose the actual locations of devices. In this second step the DMA planning concerns modification of the network connectivity structure due to the installed closed gates (Laucelli et al., 2017). Therefore, the aim is to evaluate whether the DMA planning involves change in the network domain, i.e. the formation of districts can modify the relevance of the main elements/paths into the network and the WDN vulnerability. In this way, the WDN domain analysis can represent a useful tool to quantify the feasibility of management interventions even before the hydraulic modelling also considering the modifications obtained after the DMAs planning. The strategy is applied and discussed using a real hydraulic system. The paper is organized as follows: section 2 reports the methodology, resuming the main concepts of the strategy proposed by Giustolisi et al. (2019) and those related to the DMA planning, section 3 reports the case study and an interpretation of main results and section 4 reports the conclusions.

2 METHODOLOGY

Water distribution networks (WDNs) are infrastructure networks with special characteristics because they are urban spatial networks (Barthélemy, 2011; 2018). Giustolisi et al. (2019) proposed a domain analysis of the WDN hydraulicities tailoring CNT studies and tools, in order to help in understanding the role of domain features in the emerging hydraulic behavior, which is used to support planning and management decisions. The tailoring is based on four points. (i) Considering the pipe relevance instead of the nodal one, and therefore, computing the edge betweenness and not the classical one, because the edge betweenness is more meaningful for WDNs accounting for flow path disruption. (ii) Considering pipes as material components with weights that correspond to their asset features (e.g. length, diameter, hydraulic resistance, etc.). In this way the analysis also includes the characteristics of the system domain. (iii) Considering nodes differently in order to assign the effective topological relevance to the source nodes. In fact, reservoirs and tanks represent different hydraulic elements with respect to other nodes, as a kind of hub from the hydraulic standpoint. (iv) Accounting for the directional devices, in order to consider the prior information about the known directions. Therefore, the WDN-Tailored Edge Betweenness for WDN domain analysis assumes network connectivity, pipes resistance, directional devices and tailors the source nodes with fictious edges to better capture the relevance of pipes. The tailored metric allows to rank pipe relevance and to assess in advance the importance of closing or adding a pipe in the connectivity structure based on the topological position (and hydraulic characteristics) of the occurrence. In fact, the main skeleton of the WDN is composed by a small subset of most relevant pipes, identified by means of WDN-Tailored Edge Betweenness, and an intervention which modifies that skeleton might be relevant for the domain structure. To this purpose, the paper proposes the use of the WDN-Tailored Edge Betweenness after planning DMAs to evaluate if it introduces changes in the WDN domain. The DMA planning is obtained by applying a two-steps strategy (Laucelli et al., 2017) based on the optimal segmentation design, as first step, aimed at achieving scenarios of conceptual cuts dividing the network into modules, and the optimal DMA design, that returns the decision on installing a flow meter or a closed gate valve in each conceptual cut of one optimal segmentation solution. The results, before and after the connectivity structure modification obtained with the DMAs planning, can be useful to quantify, at least partially, the importance of the intervention in advance with respect to hydraulic modelling.

3 CASE STUDY

The WDN-Tailored Edge Betweenness is applied and discussed using a large real hydraulic networked system composed of 7217 nodes, 8496 pipes and 3 reservoirs, with a length of 440 Km, whose layout is reported in Figure 1. Afterward, the centrality metric is applied and discussed using the same network after planning DMA.
3.1 DMA Planning

DMA design is a process that consists of two phases, the segmentation of the topological structure of the network, which corresponds to a conceptual phase, and the actual hydraulic division, which involves the physical installation of gate valves and flow meters. The topological segmentation is achieved by solving a bi-objective optimization problem, where the infrastructure modularity (Giustolisi and Ridolfi, 2014) and the numbers of conceptual cuts are simultaneously optimized. Increasing the number of conceptual cuts increases the value of the modularity index. All the segmentation solutions are nested into each other, which enables to switch from one solution to another, with a higher modularity index, simply by adding one or more conceptual cuts to those of the current solution. The maximum topological segmentation configuration in the real WDN has 54 modules with a number of conceptual cuts equals to 186. Starting from this segmentation solution, the second phase, i.e. the optimal DMA design (Laucelli et al., 2017), has as purpose the optimal installation of the gate valves, aimed at reducing the volumetric leakages, and of the flow meters, in minimum possible number, in each of the 186 conceptual cuts of the segmentation solution. The DMA design returned 80 solutions, each with different number of gate valves and flow meters, rate of leakage reduction and possible unsupplied demand. Figure 2 reports the DMA solution with 98 closed gates and 88 flow meters. The installation of gate valves generates several change in the WDN hydraulic behaviour, as shown in Figures 3 and 4, reporting the average nodal pressure (left), the pipe leakages (centre) and the volume in terms of background leakages and customers demand (right) for the original network and for the DMA solution, respectively. The results are detailed in the Table 1. Different distribution of flow paths for the DMA solution with respect to the original one results in a leakage reduction equal to about 46%, with technically irrelevant unsupplied demand (i.e. 4m³).
Figure 3: Average nodal pressure (left), pipe leakages (centre) and volume in terms of background leakages and customers demand (right) for the original network.

Figure 4: Average nodal pressure (left), pipe leakages (centre) and volume in terms of background leakages and customers demand (right) for the DMA solution.

Table 1. Difference in hydraulic behavior between original network and DMA solution.

<table>
<thead>
<tr>
<th></th>
<th>AVG PRESSURE [m]</th>
<th>PIPE LEAKAGES [m³/day*Km]</th>
<th>BACKGROUND LEAKAGES [m³]</th>
<th>CUSTOMER DEMAND [m³]</th>
<th>UNSUPPLIED DEMAND [m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ORIGINAL NETWORK</td>
<td>44</td>
<td>74.4</td>
<td>32,422</td>
<td>36,361</td>
<td>0</td>
</tr>
<tr>
<td>DMA SOLUTION</td>
<td>24.1</td>
<td>40.2</td>
<td>17,521</td>
<td>36,357</td>
<td>4</td>
</tr>
</tbody>
</table>

3.2 WDN-Tailored Edge Betweenness for WDN domain analysis

The domain analysis is performed for the original network and for the DMA solution using the WDN-Tailored Edge Betweenness (Giustolisi et al., 2019). The metric is computed using the hydraulic resistance as weight for the pipes, in order to include the domain characteristics of the network in the analysis. Figures 5 reports the pipe flow rates (left) and the WDN-Tailored Edge Betweenness (right) for the original network.
In order to compare the domain analysis before and after the DMA planning and to assess whether the DMA planning influences the main paths in the network, Figure 6 reports the WDN-Tailored edge betweenness for the DMA solution.

The comparison between the network before and after the DMA planning is really positive. In fact it shows that the metric identifies almost the same pipes (paths) as the most relevant both before and after the DMA planning. In both cases, the pipes with the tailored edge betweenness falling in the 5% highest values corresponds each other and quite well to the pipes with the highest 5% values of the average flow values for one-day hydraulic simulation. Therefore, it is possible to state that the WDN-Tailored Edge betweenness, just considering the domain structure of the system, identifies quite all the most important pipes as the pipes with the highest flow rates, i.e. the centrality metric is able to capture the emerging hydraulic behaviour due to the connectivity structure of the network, both before and after the DMA planning. Considering that the pipe flows depend on the boundary conditions and on mass and energy equations, the fact that the centrality metric identifies the most important pipes even after closing valve at districts, i.e. after the connectivity structure modification, means that the network domain does not change in a relevant way after the installation of closed
gates. Therefore, the DMA planning does not affect the vulnerability and the relevance of the main paths, i.e. it does not influence the network domain.

Observing Figures 5(right) and 6, it is possible noting that the topological metrics also includes information related to reservoirs and directional devices in the analysis. In fact, the main paths into the network always start from the reservoirs to reach different points into the network. In this way the network skeleton, i.e. the main structure of the network, is well defined and identified by both the hydraulic and the topological metrics. Furthermore, it is possible to remark that both metrics indicate the most relevant pipes as those close to the reservoirs, i.e. the most relevant hubs, as identified from the hydraulic analysis.

The result is well represented and confirmed by the diagram in Figure 7, reporting the WDN-Tailored edge betweenness for the original network vs. those computed for the DMA solution. The diagram shows that (i) the most relevant pipes coincide for the two solutions, (ii) differences are evidenced only in correspondence of the pipes with low values of the topological metric, i.e. not relevant pipes and, therefore, (iii) the main paths into the network are preserved. The small differences between two configurations are due to the closure of the districts and to the reconfiguration of the flows within the DMA, which is an operation that mainly involves internal pipes, i.e. elements that are not decisive in defining the network domain.

![Figure 7: Original network vs DMA solution in terms of WDN-Tailored edge betweenness.](image)

This result allows to state that the DMA planning, in addition to be a valid strategy for management and reduction of leakages in WDNs, does not involve variations in the network domain that could affect the main paths and, therefore, network vulnerability. Vice versa, it seems that the results in terms of correlation between the flow and the centrality metric are improved after the DMA planning. In fact, the Spearman correlation index (Spearman, 1904) between pipe flow and WDN-tailored edge betweenness has been evaluated, both for the original network that for the DMA solution, and the results are 0.549 and 0.588 respectively.

Finally, we can state that the flow paths identified by the hydraulic simulation (Figure 5-left) are based on mass and balance equations and boundary conditions, which are solved in the domain forced by network characteristics. This means that the domain features (connectivity structure, pipe resistance, position of reservoirs, etc.) influence the system hydraulic state over time and drive the emerging behavior of the WDN hydraulics. The influence of the domain features on the hydraulic behavior is confirmed computing the WDN-Tailored Edge Betweenness (Figure 5-right), which shows that the results are almost coincident with those obtained with the hydraulic simulation, i.e., the main paths correspond for the two metrics. It seems clear that the tailored metric represents a useful tool to understand if a network is well structured with respect to its hydraulic scopes, i.e. the information contained in the domain is relevant for the WDN hydraulics. The comparison between the network before and after the DMA planning (Figure 6) demonstrated that the installation of closed gates does not influence the vulnerability and the main paths of the network. This fact confirms the usefulness of the tailored metric in performing the domain analysis, even in presence of DMA. This further result makes the tailored metric also useful to evaluate whether design, maintenance, planning and management interventions can change the network domain of the hydraulic system in terms of vulnerability or relevance of main paths.
4 CONCLUSIONS

The present paper confirms that the WDNs hydraulic behavior is strongly dependent on the domain features which is captured by the WDN-Tailored Edge Betweenness and that the DMA planning does not involve relevant changes in the vulnerability and paths relevance with respect to the network without DMAs. The comparison between original network and DMA solution shows that: (i) the main path into the network does not change after planning DMA, as well as WDN vulnerability; (ii) the edge betweenness captures the emergent hydraulic behavior as described by pipe flow rates even after planning DMAs; (iii) the correlation between the hydraulic and the centrality metric is confirmed also considering the DMA solution. Therefore, the work confirms the usefulness of the optimal DMA planning in the management and reduction of leakages also without variations on the vulnerability of the system or on the relevance of the main paths.

Therefore, although WDN-Tailored Edge Betweenness does not replace the hydraulic simulation, it represents a useful tool for supporting WDNs analysis, design and management tasks, providing helpful indications to drive model validation, maintenance works as well as relevance of paths to plan operations. This confirms that the domain analysis remains crucial together with the hydraulic simulation, since they are complementary in analyzing WDNs.

REFERENCES