Characteristics of the oil transport network in the South of Mexico

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Characteristics of the oil transport network in the South of Mexico

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Abstract. We present a study of some organizational properties of the oil transport network of the Mexican oil company (PEMEX) in a region of the State of Tabasco. Particularly, the generalized centrality and the distribution of connectivities are calculated in order to evaluate some aspects of the structure of the network. We find that the connectivities \( k \) are characterized by a degree distribution which follows a power-law function of the form, \( P(k) \sim k^{-\lambda} \), with \( \lambda = 2.6 \). Moreover, our procedure permits to evaluate the importance of lines (ducts) and nodes, which can be wells, production headers, separation batteries and petrochemical complexes.

1. Introduction

In recent years there has been a growing interest in the study of systems that can be modelled by means of networks or interconnected systems [1–3]. Particularly, the transport systems have attracted the attention of the investigators from different areas of science, as they analyze systems to explore from the information flow and transportation of products to the movement of people. The growth of many of these systems depends on external factors, reason why the emergent configurations reflect irregular aspects. For example, it is recognized that the growth population in cities together with its spatial expansion generate the sprouting of supply routes, which are adapted to the existing ones; the same happens in systems where the transport of substances or products is necessary. In this sense, the oil transportation takes a great importance for the operation, distribution and commercialization. Moreover, the use of some optimization criteria during the design can not only impact reducing investment but also improving the efficiency of the system. There are few studies in different parts of the world related with the evaluation of the topological properties of pipeline networks for the characterization of the transport of petroleum, which represents a strategic information for any oil company. To our knowledge, the pipeline transport network of the Mexican oil company (Pemex) has not been analyzed by means of network methodologies, where some topologic and organizational properties can be extracted, providing information of the transport [4,5].

In the present study the oil pipeline network is modeled like a complex network, where the nodes represent wells, production header, separation batteries, petrochemical complexes or terminals and the connections are equivalent to lines of ducts connecting the nodes. Our results show that the

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connectivities in the pipeline network are characterized by a degree distribution which follows a power-law function, denoting a scale-free character in the connectivities. We also found that the generalized centrality provides a criterion to identify the importance of both nodes or links, in terms of dynamical situations like the transport of oil in a pipeline network. The paper is organized as follows. In Section 2, we present a description of the pipeline network and the main results are also described. Finally, some final remarks are given in the Conclusions.

2. Results

2.1. Degree distribution of the oil pipeline network

Usually a network is conceived as a set of nodes which are connected by means of links. The degree of a node is defined as the number of links entering or exiting a node, when the connections are not directed. The degree distribution $P(k)$, where $k$ represents the degree, allows to describe the connectivity of the network, that is, if the relative frequencies are plotted against the degree, one obtains a distribution that characterizes the network, therefore, the structure of $P(k)$ offers information about how connections [6,8] are distributed. It is known that random networks have a characteristic scale in the connectivity, with a degree distribution of the Poisson's type, where the average degree is representative for the connectivity of the network. Many other networks observed in the real world do not have a single scale in the connectivities, i.e., they are scale-free networks, in which many nodes with few connections coexist with a small number of nodes with high connectivity (hubs).

Recent studies of the transport properties in complex networks have shown that scale-free networks have better conditions for transport compared to random networks, this is mainly related to the presence of hubs in scale-free configurations [9,10]. A simplified analysis of transport in a network, can be conceived as flow subject to the direction of each link and a potential difference between nodes. With this framework, the problem of finding the features that improve or worsen transportation, satisfying capacity constraints on the links and flow conservation at intermediate nodes [11,12], is an important topic and can be used to model and characterize some real transportation networks.

Here, we study the emergent configuration of an oil pipeline network. First, we recall that this type of network is a directed network because the oil is collected at the wellhead and from the wellhead it is pumped through a pipe to other intermediate sites, and finally, is discharged at its final destination, which in most of the cases is a refinery. We collected data of the pipeline network for the oil transportation from the wells to the refinery. This infrastructure is owned and operated by PEMEX, the Mexican oil company, and it is located in the South of Mexico. Specifically, our analysis is based on the Bellota-Jujo (B-J) system located in the area close to Comalcalco City in the Southern state of Tabasco [5]. The oil fields are located in different municipalities. This transport infrastructure is comprised by 165 wells, 26 production headers, 13 separation batteries and 3 petrochemical complexes, which correspond to nodes connected by pipelines (see figure 1 and 2).
Figure 1. Oil production system in the State of Tabasco, Mexico. We show the location of the nodes: wells (black squares), production headers (blue circles), separation batteries (red squares) and petrochemical complexes (green squares).

Figure 2. Representation of the oil transportation network. Here the nodes represent wells (yellow), production headers (red), separation batteries (green) and petrochemical complexes (blue).

The corresponding network is constructed and depicted in figure 2. Here, we observe that a few nodes (production headers colored in red) tend to have more connections. This visualization suggests that there are a variety of ranges for the connectivities, and especially if one considers the incoming or outgoing links. In order to characterize the connectivities, we first consider the incoming degrees and calculate the degree distribution $P(k)$, with $k$ the in-degree. The results presented in figure 3 show a clear indication that the network topology for the system, is a scale-free configuration. More precisely, the incoming degree distribution can be described as a power law function $P(k) \sim k^{-\lambda}$, with $\lambda = 2.6 \pm 0.03$ (see figure 3). It is worth to mention that the distribution for the outgoing degrees is very simple, because all the nodes, except petrochemical complexes, have out-degree equal to one.

2.2. The generalized centrality

In order to explore the topological properties of the transport, beyond the description offered by the distribution of connectivities, we evaluate the behavior of the transport in terms of the variables of design
and the capacities installed in the pipes that compose the network. The B-J oil transport network expands on hundreds of kilometers with different measures in diameter that go from the 3 inches until the 36 inches at the final node. In order to evaluate the pipeline capacity for transportation, in figure 4 we show the behavior of the flow (in barrels per day) in terms of the diameter of pipes entering or leaving a node. A great dispersion of the data is observed for points corresponding to wells, however, an increasing tendency can be identified for the other nodes (production headers, separation batteries and petrochemical complex). The best fit to the data in a log-log scale, excluding wells, is $\gamma = 1.95 \pm 0.13$, which is general agreement with values reported for real pipeline systems [16].

Figure 3. Log-log plot of the degree distribution vs. in-degree for the B-J oil transportation network. The solid line corresponds to the best fit with exponent $\lambda = 2.6$.

Figure 4. Plot of flow vs. diameter for the B-J system in a log-log scale. We show separately the cases of pipelines entering or existing different nodes. As expected, a growing trend is observed for the flow when the diameter is increased, suggesting that there is a power-law relationship, the straight line is a linear regression of the data, excluding wells. The value of the exponent is $\gamma = 1.95$.

Next, we evaluate the generalized centrality proposed in reference [16], which describes the topological importance of a specific connection within a transport network with appropriate information of the flows between sources and sinks. Particularly, for the oil transport network, the generalized centrality gives information about the importance of pipelines, which connect nodes (wells, production header, separation batteries or petrochemical complex). Formally, the generalized centrality of the connection $e_{ij}$ is given by the following expression [16]:

$$G_{ij}^f = \sum_{e_{ST} \in E} \sum_{s \in V_s, t \in V_T} \frac{f_{ST}}{|V_s||V_T|} \frac{\sigma_{ST}(e_{ij})}{\sigma_{ST}}$$

where $E$ is the set of links in the network; $V_s$ is the set of source nodes predecessors; $V_T$ is the set of sink nodes; $\sigma_{ST}$ is the number of shortest-paths from node origin $s$ to target node $t$; $\sigma(e_{ij})$ is the number of shortest-paths from $s$ to $t$, passing through the connection $e_{ij}$, and $f_{ST}$ is the existing flow in the connection $e(i,j)$. 
For simplicity, we consider a normalization of the generalized centrality given by:

\[ G_{ij}^f = \frac{G_{ij}^f}{\max G_{ij}^f} \]

where \( \max G_{ij}^f \) represents the maximum value of the set of connections.

The values of \( G_{ij} \) are calculated for all the links in the B-J system. We find that the distribution of the generalized centrality values can be described by a power-law function, \( H(G) \sim G^\beta \), with exponent \( \beta = 2.5 \pm 0.05 \) (see figure 5a), indicating that there is no preferential scale for the centrality and a few connections are responsible of high values for this quantity.

**Figure 5.** (a) Probability distribution of the generalized centrality in a log-log scale. The power-law fit for the data gives an exponent \( \alpha = 2.5 \). (b) Log-log plot of the generalized centrality vs. flow for the B-J system. The straight line is a regression of the data (excluding wells) with slope close to 1. We notice that for low values of the flow, there is more dispersion for the points corresponding to wells.

Moreover, when we evaluate the generalized centrality in terms of the flow entering or leaving a node, we find that there is an almost linear relationship at large values of both quantities (see figure 5b). Specifically, for those nodes connected by pipelines with high flow values (production headers, batteries and petrochemical complex), the corresponding centralities are proportional, whereas more dispersion is observed for wells. Finally, we construct a representation of the centrality values, i.e., we plotted the real B-J oil pipeline system and related the color of each pipeline proportional to its generalized centrality according to the colorbar (see figure 6). We remark that the highest value is associated to the link El Misterio-Cactus, which is responsible of handling a major load.
3. Conclusions

We have studied the oil transport network from the B-J system. Our results shown that the degree distribution is characterized by a scale-free behavior, where a few nodes have high number of connections, which correspond to the production headers since they are connected to several wells. This finding is not unexpected, since different studies have reported the emergence of scale-free topologies in many man-made systems [1,13,16]. In our case, the growth of the oil transport network is strongly influenced by spatial distribution of wells and also economic constraints. By means of the generalized centrality, we have estimated the importance of links in terms of the flow it can handle. Interestingly, the distribution of centrality values also follows a power-law function, which indicates that there is no a characteristic scale for the centrality. Finally, we remark that this type of analysis is of great importance in order to understand the role of the topology in the pipeline transport system, with implications over the design and evaluation of the system's efficiency.

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References