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Evolutionary simulation of complex networks' structures with specific functional properties

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Thorough studies of technological and biological systems have revealed that the inherent networking structures of those systems possess similar topological properties, like node degree distribution or small-world effect, regardless of the context to which those systems are related. Based on that knowledge, there have been numerous attempts to develop models that capture particular topological properties of observed complex networks, although little attention has been paid to developing models with specific functional properties. The present paper proposes a method for the simulation of networks' structures with functional characteristics of interest using a heuristic evolutionary approach and utilizing a Simulated Annealing algorithm. An experimental study is carried out with a US air transportation network and synthetic social networks with known properties.

1. Introduction

To a large extent, complex systems could be described as networks in which nodes, representing some entities of the systems, are connected according to relations, and are established between those entities within the systems. A wide set of complex network models has been developed over last twenty years; these include the Barabasi–Albert [1] model of a scale-free network, the Watts–Strogatz model of a small-world network [23], the Erdos–Renyi random graph model [9], and others [14,6]. Those models allow us to model structures that, with various precision, mimic real-world structures and explain the nature of their growth and changes.

These models are useful when it is known which characteristics the model network should have. However, in many cases [17,22] there is no complete data set on complex network structure. Hence, it might be

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impossible to evaluate topological properties and choose an appropriate model that implements them in modeled structures. At the same time, the functional properties of networks, characterized by outcomes of processes that happen in complex networks, can sometimes be easily obtained by data mining, surveys, and census data [4]. Another drawback of current complex networks' models is related to a fixed algorithm, which assigns attributes to the model that define the construction process of a network structure: a single complex network model can provide a finite space of solutions, and does not favor a tweaking of obtainable properties.

We propose a method to simulate network structure based on functional properties of the network of interest. In previous studies, it was shown that some problems of process design [5], structure design in general, and network design in particular [12] can be solved with soft computing techniques such as heuristic optimization algorithms. For example, the chip placement problem was successfully solved with the Simulated Annealing algorithm [13], which was applied for the design of transportation networks [16], pressure relief header networks, and heat exchanger networks [8], as well.

The success of the heuristic approach to network design suggests an idea to apply the same approach to the problem of network structures modeling based on known functional characteristics and without prior knowledge of its topological properties, such as clustering coefficient, degree distribution, etc. The present work demonstrates the efficiency of the method for modeling general network structures using an evolutionary approach based on the Simulated Annealing algorithm, evaluated by its flexibility and its ability to realize the desired functional properties in modeled structures to the available degree.

2. Background

Let us consider the most common static models of complex networks. They are represented as a set of algorithms for the simulation of complex networks with a fixed structure.

Erdos–Renyi model. In general, the random graph model assumes that a certain plurality of network parameters is fixed, but otherwise, this is a random network structure [3]. The simplest example of such a network is a graph that is randomly selected from the set of all graphs that have N nodes and m edges. This network is usually denoted as $G(N, M)$. There is the second variant of the Erdos–Renyi (ER) random graph model. It is the $G(N, P)$ model: a graph is constructed using the random connections. Each edge appears with probability p in the graph. The networks, such as $G(N, P)$, have been studied and described in the studies of Erdos and Renyi [9,20]. The Erdos–Renyi random graph model describes an undirected graph. The choice of this model is reasonable since, in some experiments, the topological features of the imitated networks are not known.

Configuration model. The Configuration Model (CM) allows building the random graph with a particular distribution of nodes' degrees [2,19]. Thus, by using a CM, we can construct networks with an arbitrary degree distribution. The feature of this algorithm is the possibility of an appearance of multiple edges and loops, which is not typical for other models of networks.

Watts and Strogatz model (Small Worlds model). The small world model was proposed and discussed in the works of Watts and Strogatz (WS) [23,22]. This model tries to reproduce two features that are characteristic of real networks: short average path lengths and high clustering. Average path length shows the average number of steps required to travel from one node of the network to another. The clustering coefficient shows which nodes in a graph tend to cluster together. The Watts and Strogatz model has a fixed number of nodes and thus is not used to model network growth.

Barabasi–Albert model. The Barabasi–Albert (BA) model is one of the several models with a power-law distribution; these generate scale-free networks. This means that they have a power-law degree distribution, whereas the models of random graphs (WS and ER) do not have this distribution. This model includes two general important concepts: the growth of network and the principle of preferential attachment. Both concepts are well represented in real-world networks [1].