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The method of leader's overthrow in networks based on Shapley value

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ABSTRACT

Quantitative methods for leaders' detection and overthrow are useful tools for decision-making in many real-life social networks. In the given research, we present algorithms that detect and overthrow the most influential node to the weaker leadership positions following the greedy method in terms of structural modifications. We employ the concept of Shapley value from the area of cooperative game theory to measure a node's leadership and to develop the leader's overthrow algorithms. Specifically, we introduce a quantitative approach to analyze prospective structural modifications in social networks to make the initially identified network leader less influential. The resulting mechanism is based on the symbiosis of game-theoretic and algorithmic concepts. It presents a useful tool for the technical analysis of the primary structural data in the initial steps of multifaceted quantitative network analysis where the raw data (i.e., linkages) is frequently the only knowledge about interrelations in social networks.

1. Introduction

The variety of game and graph theoretical approaches plays an important role in formalizing the leadership of agents in social networks based on the analysis of node centrality metrics. In terms of practical use, one of the first research applications of centrality measures was introduced in the 1940s at the Group Networks Laboratory, M.I.T. Later, Cohn & Marriott [9] applied different centrality metrics to analyze the diversity of Indian social life. Pitts [32] used centrality-based concepts for examination of communication paths in the context of urban development while Czepiel [12] applied centrality computation in the analysis of a technological innovation in the steel industry. The practical application of centrality metrics has grown fast in the last fifty years. For example, Moore, Eng & Daniel [29] used centrality scores for the estimation of aid coordination between the non-governmental organizations (NGOs) in Mozambique (i.e., NGOs involved in the flood operations). Estrada & Bodin [14] used network centrality metrics to manage landscape connectivity. Faris & Felmlee [15] explored gender segregation and cross-gender aggression based on centrality measures.

In the given research, we present a quantitative analysis of leadership in social networks employing the idea of network centrality. We use the term “node” as an equivalent to the terms “agent” and “player” since we do quantitative social network analysis (SNA) based on graph and game theoretical approaches.

Agents' leadership is one of the core ideas in SNA. Different evaluation methods exist. Degree [17], betweenness [3,16], and closeness [5,34] are the most widely known metrics that assess the structural centralities of nodes. The algorithmic measures of nodes' leadership are well presented in Kleinberg [26] and Page et al. [31]; where the notion of leadership is given based on the analysis of link structures. An interesting approach to characterize the role of nodes within networks is given by Scripps et al. [38]; where the community-based metric in the symbiosis with the degree-based measure is introduced in the context of nodes' roles classification. The problem of leadership analysis in networks is well described by Balkundi & Kilduff [4] and Hoppe & Reinelt [23].

In contrast, there is yet another problem of understanding how the network's structure should be efficiently modified in order to overthrow the current network leader to the weaker positions.

Generally, modern social networks are presented by large-scale structures with poorly formalized data flows due to their uncertain social nature [41]. Consequently, basic information about a network structure (i.e., presence/absence of links between nodes) is often only the well-formalized data about the social network. In this case, network structure presents basic knowledge about interrelations that can be employed for the decision-making related to a network's modifications.

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Consider large-scale terrorist networks that are often characterized by the lack of knowledge about specific information flows within existing interrelations. On the initial steps of network analysis, the structural factor plays a key role for understanding interrelations and detecting agents' leadership. In networks, such as criminal networks with hidden patterns, or money laundering networks, the overthrow of the detected leader may seriously damage the network structure or even bring about irreversible destruction [13,24,35].

In this paper, we consider the case when all nodes in the network participate in the process of the leader's overthrow. Specifically, the main goal of the given research is to analyze what sufficient set of links has to be established in a network (based on the greedy approach) in order to decrease the leader's influence on other nodes.

Agents establish links between each other for different socio-economic reasons depending on the nature of the social network. For example, in organizational networks [11], agents compete for leadership positions in informal organizational networks by creating new relations in order to improve their leadership positions in the formal organizational structures. Building leadership is a competitive process that is based on establishing new relations and overthrowing the existing leaders. Another example is related to criminal and terrorist networks. A sleeper agent might incite other agents to create new relations in order to improve their leadership position and, simultaneously, to weaken current network leaders [37].

Two agents in a network are motivated to create a link between each other only if both of them make some profit from it. Specifically, in our research we consider profit as an improvement of an agent's leadership. To measure the level of a node's leadership we employ the concept of Shapley value [39] from the area of cooperative games. Specifically, we use the Shapley value (SV) centrality metric developed by Aadithya et al. [1].

In the context of our quantitative network analysis, we determine the leader as a node that has the highest SV. This means that it has the highest SV-based leadership in the network where cooperation is presented by links between nodes. The leader's overthrow is a procedure of structural modifications that results in the leader's SV-decrease in terms of the distribution of a total surplus generated by the coalition of all nodes.

The quantitative analysis of agents' leadership in terms of SV distribution allows us to build potential scenarios for structural modifications in a network. As a result, we get primary information as part of the multi-faceted leadership analysis in networks. This primary information regarding the leadership distribution (in terms of SV) does not play a key role in the decision-making process for network modifications, but it reflects quantitative SV-based leadership distribution based on the structural factor.

In the given research, we show the advantages of the SV-based concept compared to the traditional centrality metrics and explain why SV is employed to measure leadership in networks. Based on the given SV-based game theoretic approach we develop two overthrow algorithms that establish sets of links to overthrow the initial leader with the highest SV to the weaker positions.

Next, we test the SV-based algorithms based on the trivial network topologies and on the real-world structures retrieved from the co-authorship networks of the Norwegian School of Economics (NHH) and BI Norwegian Business School [6].

The scientific finding of the given research is based on the idea of building a quantitative mechanism that detects prospective structural modifications in social networks based on the game theoretic approach. The advantage of the SV-based game theoretic approach (compared to classical well-known network metrics) is presented in the following section.

2. Shapley value as the network's centrality metric

Shapley value is one of the fundamental concepts of game theory [33]. The core idea of SV is the payoffs' distribution among players according to their personal contributions to the overall gain in a cooperative game. Since SV measures players' leadership based on their mutual cooperation, it is applicable in the domain of social network analysis. Specifically, it reflects the real-world players' interrelations since it counts mutual influence of players in all possible coalitions in networks.

For large-scale networks with lack of detailed information regarding internal processes, the structural factor becomes important for a quantitative assessment of the leadership potential of nodes. Often, structure is the only well explored factor. Therefore, it is important to have an efficient measure that evaluates node leadership based on the network structural characteristics.

To understand why the concept of Shapley value is employed for the network leadership analysis, it is necessary to understand when it is useful to employ it.

The SV-based centrality metric is not the unique or the only solution to estimate leadership. Considering conventional centrality metrics, e.g., those based on node degree, closeness, and betweenness, it should be specified that each of them reflects a node's leadership depending on the particular application. Depending on the context of the problem, an appropriate centrality metric should be employed. Consider an abstract transportation network, where the set of locations (i.e., nodes) is connected by roads (i.e., links). The degree-centrality reflects an immediate influential power showing how many locations are directly reachable from the current node, but it does not count the global network structure, because it takes into consideration only the neighboring nodes approachable in one hop (i.e., within one-link distance). The closeness centrality measures how fast it is possible to travel between different locations in terms of the overall network. It is based on the calculation of the inverse sum of the node's shortest distances to all other nodes. The betweenness centrality reflects the leadership of the node in terms of how often it is required to go through the location along the shortest route between two other locations. In many real-life networks there is a great proportion of nodes that do not appear on the shortest paths between any other two nodes [30]. This means that many nodes can get the betweenness value equal or close to zero. Since closeness and betweenness centralities take into account the overall network structure, they are more advanced measures compared to the degree centrality, but "prohibitively expensive to compute, and thus impractical for large networks" [25].

The efficiency of conventional centrality metrics depends on the application area. Nevertheless, they have a generic nature that is characterized by an "individualistic" measurement approach. This means that they "fail to recognize that in many network applications, it is not sufficient to merely understand the relative importance of nodes as *stand-alone* entities. Rather, the key requirement is to understand the importance of each node in terms of its utility when combined with other nodes" [1]. This means that conventional centrality metrics do not consider the interdependencies of nodes' failures. They reflect the resulting effect (i.e., after-effect) of multi-node failures in terms of a network's structure. It is important to specify a key point that "such an approach is inadequate because of *synergies* that may occur if the functioning of nodes is considered in groups" [28]. The SV-based centrality metric counts the mutual effect of all possible nodes' combinations measuring the leadership of nodes within a graph [19].

Aadithya [1] study found the following: