Evolution of Global Crude Oil Dependence: A Weighted-Directed Graph Analysis

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***Abstract*—Interdependent networks is no longer a new term: it has already become a part of day-to-day life of the society. Therefore, it is paramount to assess the resilience of such complex interdependency in networks. Besides considering the usual unidirectional and bidirectional links among the interdependent networks, weights of links also impose realistic constraints for accurate network performance evaluation. We develop a framework to analyze the robustness of interdependent networks. Each element in the network is attacked based on graph centrality metrics. Furthermore, we introduce weight to links to provide better accuracy in our analysis. To generate the simulation model for our analysis, we construct a weighted and directed graph of imports and exports of crude petroleum of all the countries across the globe. Using this methodology, we can evaluate the realistic interdependent topologies under attacks. Our graph-theoretic methodology can be a useful tool to develop national economy policies.**

***Keywords*-interdependent networks, directed graph, time-evolution graph, resilience, robustness, centrality.**

I. Introduction and Motivation

Interdependent networks have become a part of day-to-day life of the society. An interdependency is a mutual relationship between two networks, which means the functionality of one network is influenced by another network. In such interdependent networks, when nodes in one network fail, they may lead to the failure of dependent nodes in the same network as well as other networks leading to a series of failures [1].

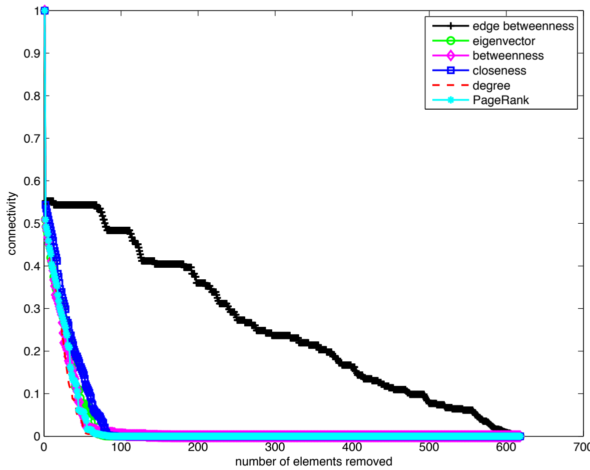
From the observations of previous disasters and to meet the future requirements, robustness of the interdependent network to cascading failures emerges as the primary goal in designing and analyzing such complex interconnected systems. Many tools have already been developed to study cascading failures, but they are more focused on the behavior of individual networks in such conditions. A far more neglected area is the interdependency among the multiple networks, including potential cascading effects [2], [3]. This allows potential attackers to exploit the vulnerabilities of the network causing series of failures in the network.

In this paper, we applied our own framework developed in [4], [5] to analyze *connectivity* of interdependent networks. We model the interdependencies between nodes in a network as a *directional graph*. We apply our framework to the dataset consisting of the crude oil imports and exports of all the countries across the globe, to analyze the connectivity under targeted attacks. The interdependency between the countries is by the means of imports and exports from one country to another. To provide better accuracy, we are introducing weight to the links in the network. The critical nodes and links in interdependent networks are determined using graph centrality metrics such as degree, betweenness, closeness, eigenvector, and PageRank. We show that the rankings of critical nodes vary over different attack strategies. This framework can help us understand and study the resilience of complex interdependent networks.

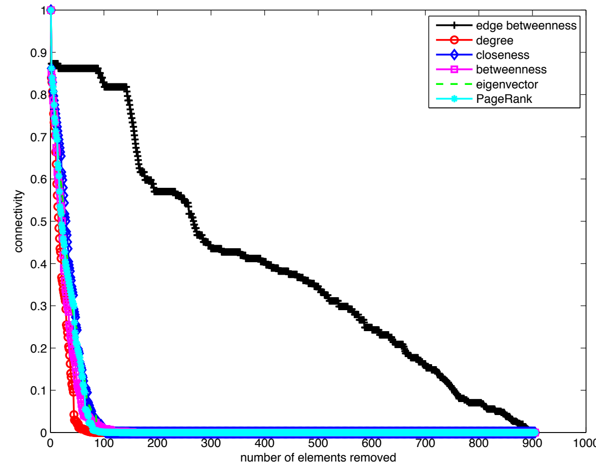
II. Topological Dataset

We apply our framework on the simulation model graph in which all the countries in the world are dependent or interdependent on other countries. To make our analysis more accurate, we construct the graph from the real dataset consisting of imports and exports of crude petroleum of all the countries across the globe. The dataset is taken from the tool Observatory of Economic Complexity developed by the MIT Media Lab Macro Connections group [6], [7].

In this graph, we designate each country as a node and the connectivity between the countries as directed links. If there is an interdependency (i.e. mutual dependency) between two countries, then we designate this as a *bidirectional* link. If a country is dependent on another, but this dependency is not mutual then we designate this relation via a *unidirectional* link. The interdependencies between countries is based on the import and export values of one country to another country. If there is no dependency, that simply means there is no import or export to that country. To analyze the results, we construct the time evolution of the interdependent graph from 1995 to 2012. The interdependency graphs are constructed with 168 nodes (i.e. countries) and 666 links for the dataset in 1995 and with 987 links with the same number of nodes for the dataset in 2012 including unidirectional and bidirectional links. We will analyze the dataset between years 1995 and 2012 in our future work.



(a) Connectivity of global crude oil graph in 1995



(b) Connectivity of global crude oil graph in 2012

Fig. 1. Connectivity under centrality attacks

III. Analysis

We apply the constructed exports and imports graphs on our framework that analyzes interdependent networks. Nodes and links are removed adaptively – graph metrics are recalculated after each iteration of node removal – based on centrality metrics [1]. We evaluate connectivity as a measure of network resilience. We also rank the top ten counties based on their centrality importance (not shown due to space constraints).

The effect of attacks on the nodes based on their degree, closeness, betweenness, eigenvector, and PageRank centrality is shown in Figure 1. We see that all the node centrality attacks follow a similar trend in connectivity degradation and and being diversified after each attack. In the 1995 dataset, degree centrality along with closeness and PageRank eliminated the connectivity of the interdependent graph in fewer number of attacks compared to other metrics, taking only 93 attacks, followed by eigenvector centrality and betweenness centrality, as shown Figure 1a. Due to less connectivity and longer paths in 1995, betweenness and eigenvector centrality are less efficient in decrementing the connectivity of the graph. For the 2012 dataset, degree centrality eliminated the connectivity of the interdependent graph in fewer number of attacks compared to other metrics in 104 attacks, followed by closeness, PageRank, eigenvector, and betweenness centrality, as shown in Figure 1b. Degree centrality has a greater impact in degrading the connectivity of the graph because removing a node with higher interdependencies results in the removal of a large number of flows.

The node-centrality attacks impact the connectivity at a higher rate compared to an edge betweenness attack, since removing a node disconnects all incident edges connected to that node. Moreover, as soon as a node is removed, we can see the degradation in connectivity immediately, whereas it takes the removal of 617 and 904 links to see connectivity degradation to 0 in the 1995 and 2012 dataset respectively.

IV. Conclusions and Future Work

In this paper, we generated a framework for analyzing the connectivity of interdependent networks. We applied our framework on the constructed weighted-directed graphs of imports/exports of global crude oil to analyze the interdependent network performance. Based on our comparative analysis on both the graphs from 1995 and 2012, degree, closeness, and PageRank centralities are proved to be the most effective metrics to analyze the connectivity of a graph. The US has been the most important country in the global connectivity of the graph. Adding to that, node centralities had a greater impact on the network than the edge centralities for the obvious reasons, removing a node disconnects all the links attached to it whereas removing a link just affects the nodes connected to that edge. The application of graph-theory can be fruitful in developing a sustainable national economic policy.

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