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Serviceability of large-Scale systems

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ABSTRACT

One of the most important research fields of network sciences is the robustness of networks. A recently answered important question was the following: Which network topologies are more resistant to random malfunctions and/or direct attacks? Nevertheless, until now, “which system topology can be maintained and how to manage maintenance more efficiently and effectively” have been open questions. However, these questions are the keys both to designing large-scale systems and to scheduling maintenance tasks. This paper proposes a new means to analyze the maintainability of a large system by combining two kinds of networks, i.e., the reliability diagram of the system (1) and the network of scheduled maintenance tasks (2). This paper shows how to assign maintenance task(s) to a system component to increase the reliability of the system. With the proposed method, the maintainability of large-scale systems can be analyzed.

1. Introduction

The robustness and resistance of networks are widely studied in network science (see [1] for an excellent review). Scholars showed that so-called small-world[1] (hereinafter SW, e.g., (electrical) power grids, see [3]) and scale-free (SF, e.g., the Internet and social networks, see [4]) networks are more resistant to random failures than random networks [4,5].

SW and SF networks have common features (see [6] for a great synthesis). These networks can be measured by the average shortest path length, as these networks allow limiting the number of stops (intermediate nodes) between two given nodes, on average. In addition, these networks contain many hubs (bridge nodes) [7]. However, SW and SF networks contain only a few large degree nodes (hubs, in this study, power plants); therefore, these networks (similar to power grids) are slightly resistant to direct attacks [8]. The distribution degree of the SF and, usually, SW networks follows a power law, at least asymptotically. That is, the fraction $P(k)$ of nodes in the network having k connections to other nodes obeys $P(k) \sim k^{-\gamma}$, where γ is a parameter that is typically in the range of [2, 3] for SF networks, although it may occasionally lie outside these bounds. The structure of the power grid can be characterized usually as a planar network (meaning edges do not cross each other). This network is an SF network instead of an SW network; however, the degree of distribution can also follow a power function, and the typical parameter $\gamma \in [1, 2]$. A planar network is more physically constrained and thus is more assortative, with a higher probability of containing a giant component (i.e., a connected subgraph containing a majority of the nodes) [7]. Similar to the SF networks, these networks are also less vulnerable to random failures than random networks and slightly more resistant to a direct attack than SF networks [9].

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[1] SW networks exhibit a small average path length between pairs of nodes. For an excellent classification of small-world networks, see Amaral et al. [2].

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Owing to the knowledge of network topologies, we can now generate robust networks [8], or we can improve an existing system network (see, e.g., [10,11]) to make them more resistant. Adequate network topologies can help us reduce the probability of system failures. However, an open question remains: which *kinds of large-scale systems can be maintained more effectively? Are more robust large-scale systems more effectively maintainable?*

The challenge of this exploration is to address different kinds of structures at the same time. For example, to schedule maintenance tasks,[2] at least two different kinds of structure are usually required. One structure (or one network) (1) is needed to describe the system (e.g., the production system, the Internet, or the electrical power grid), and the other structure (2) is needed for specifying the relation of activities. Therefore, instead of only network thinking (which focuses only on one structure), we need multi-structural thinking. In addition to network topology, we should focus on the interaction between structures. In maintenance management, we need at least two different kinds of structures (see Fig. 1), which are variously organized.

1. The reliability block diagram (RBD)[3] of a production system can be described as a simple so-called serial/parallel (hereinafter S/P) network [15], while a power grid, the Internet and a communication network can follow a scale-free (SF), a small-world (SW) or other networks [5].
2. Small- to large-scale plans can be characterized as the so-called random networks.[4]

In a maintenance plan for all (parts) of system components, we assign at least one so-called corrective/preventive maintenance task (see Fig. 1). If these maintenance activities are completed, the reliability or availability of the maintained equipment will be increased. Therefore, these structure elements impact each other.

The other challenge of using networks in maintenance management is that the maintenance plans should be characterized as a flexible logic plan (as in [17]). Completing all possible maintenance activities has rarely occurred. Instead, the task is to select adequate maintenance tasks to improve system reliability and/or system availability while maintaining budget and deadlines.

A maintenance task can be completed by different means, the so-called completion mode. Generally, we can assume that a lower task duration requires higher cost, and higher growth of component reliability takes more time. If the set of activities is fixed, this problem is a discrete version of a time-quality-cost trade-off problem, where the quality parameter is the growth of component reliability. The discrete version of the time-cost trade-off problem is currently an NP-hard problem [18]; however, in this case, there are additional quality (i.e., growth of component reliability) parameters assigned to maintenance tasks. Moreover, the problem is further complicated by addressing flexible dependencies and uncertain task occurrences. Since [19]'s algorithm can address maintenance plans, this method can only be used for maintaining production systems, which can be characterized as serial-parallel networks.

In this paper, we extend this algorithm to analyze the maintainability of large-scale systems and support decision-makers in finding the most adequate multi-structure.

2. Analyzing the serviceability of the system

In this paper, we focused on the serviceability of the different kinds of system.

According to Blanchard et al. [20], *Maintainabilitydetermines the probability that a failed equipment, machine (=system component), or a system can be restored to its normal operable state within a given make-span, using the prescribed practices and procedures. Its two main components are:*

- *Serviceability (ease of conducting scheduled inspections and servicing) and*
- *Repairability (ease of restoring service after a failure).*

This paper mainly focuses on *serviceability*. In accordance with Lam et. al [12], we consider the time, cost and resource constraints of a schedule of maintenance tasks. At the same time, upon specifying resource availabilities, budgets and deadlines, the minimal growth of system reliability[5] is also specified. The target function was to find the minimal make-span considering the given budget of a schedule and the minimal growth of the system reliability.

2.1. Calculating system reliability

To schedule maintenance tasks, the first step is to characterize the system. One of the most frequently used modeling techniques is the reliability block diagram (RBD). To model a simple production system, an RBD is drawn as a series of blocks connected in parallel or in sequential configuration. Each block represents a component of the system with a failure rate. Parallel paths are redundant, meaning that all the parallel paths must fail for the network to fail. This “redundancy” is important for critical equipment, e.g., in a power plant.

[2] See an excellent review of the specialties of scheduling maintenance tasks in [12].

[3] The reliability block diagram (RBD) is a diagrammatic method for showing how component reliability contributes to the success or failure of a system (see, e.g., [13,14]).

[4] For further literature about random networks, see [16].

[5] In this study, the quality parameter considered is the growth of system reliability.