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Heuristic approximation and computational algorithms for closed networks: A case study in open-pit mining

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ABSTRACT

We investigate a fundamental model from open-pit mining which is a cyclic system consisting of an (unreliable) shovel, trucks travelling loaded, unloading facility, and trucks travelling back empty. The interaction of these subsystems determines the mean number of trucks loaded per time unit — the capacity of the shovel, which is a fundamental quantity of interest. To determine this capacity we need the stationary probability that the shovel is idle. Because an exact analysis of the performance of the system is out of reach, besides of simulations there are various approximation algorithms proposed in the literature, which stem from computer science and can be characterized as general purpose algorithms.

We propose for solving the special problem under mining conditions an extremely simple alternative algorithm. Comparison with several general purpose algorithms shows that for realistic situations in the open-pit mining application the special algorithm outperforms the precision of general purpose algorithms. This holds even if the general purpose algorithms incorporate more details of the underlying models than our simple algorithm, which is based on a strongly reduced model. The comparison and assessment is done with extensive simulations on a level of detail which the general purpose algorithms are able to cover.

We discuss the application of our proposed algorithms to other applications. It turns out that our algorithms are analogues to Norton's Theorem for a large class of general transportation systems.

1. Introduction

Closed networks of queues served in many areas as models to investigate performance and reliability of systems. For so-called product form networks there exist well developed tool sets for such investigations, see the classical papers on Jackson networks [1] and Gordon and Newell networks [2] and their generalizations by Baskett, Chandy, Muntz, and Palacios [3] and Kelly [4]. The resulting product form calculus provides closed form expressions for the most important performance metrics.

If the problem setting enforces to deviate from the properties needed to hold for using product form calculus (e.g. exponential distributions, independence), often no closed analytical results for performance and reliability analysis exist, but

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various approximation methods are developed. A survey is the monograph by Bolch, Greiner, de Meer, and Trivedi [5]. Easy access is via the textbook of Gautam [6].

The algorithms described in these books are mostly developed by researchers from the field of computer and communications networks, but are claimed to be general purpose algorithms, e.g. to compute throughput of any suitably defined network. Indeed, this has been proven in many applications, e.g. in production and logistics networks.

The motivating example of our paper is located in a different area. A particular model from open-pit mining had to be analysed: We are interested in the annual capacity of a (large) shovel in open-pit mining. Given the characteristics of the system, e.g. loading and unloading times, capacities of transport units, transportation times, which are prescribed as random variables, due to changing environment conditions and inherent process variability, we are interested in the capacity as a function of the number of trucks cycling in the system. This would open the possibility to determine a cost-optimal number of trucks, but we shall not undertake this step in this paper. From the very beginning, experience of engineers in this field excluded product form models from being realistic. From a queueing-theoretical point of view the reason for usage for a non-product-form model is that loading at the shovel (and unloading as well) in such systems are performed according to First-Come–First-Served (FCFS) regime, while the loading and unloading times are not exponential. To be more precise: The coefficient of variation of the service times is considerably smaller than one.

This suggests to apply one or more of the mentioned general purpose approximation algorithms at hand.

A comparison with results obtained by detailed simulation revealed that these algorithms often do not perform well in this special application. As will come out from our study this is inherent in the model and the structure of the underlying problem. If the side constraints imposed from the mining systems are fulfilled in other applications, this drawback will be visible as well. Because of the high values to invest the question arises whether it is possible to develop a specialized algorithm which can provide reliable performance predictions before investment decisions are made. Indeed, for this particular case a heuristic approximation from Dietrich Stoyan & Helga Stoyan (1971) is at hand. This algorithm was developed for the special problem in open-pit mining and related systems' analysis and is simple. Because it seems to be not accessible to the international community we revisit this algorithm here and compare it with the mentioned general purpose algorithms. It turned out that with today's computing systems there are no runtime problems for the considered algorithms. Therefore we are only interested in precision, which is here defined by the distance from simulation outcomes from performance metrics of interest. It was surprising to us that in a realistic parameter setting despite of its simplicity the algorithm outperforms with a shovel which is reliable (such that possible rare breakdowns can be neglected) all general purpose algorithms we tackled. This parameter setting is characterized by relatively moderate variability in the service process. At present we do not have any theoretical underpinning of this surprising observation.

To be honest we show that with high variability in the system direct application of this new algorithm is not recommendable. We will discuss this in detail and find out that our observation is in line with recommendations for to apply queueing models for performance evaluation in open-pit mining systems: If the shovel suffers from e.g. bad environment conditions or internal unreliability which leads to a relevant breakdown rate our experiments enforced us to modify the new algorithm. We incorporate an idea of Carmichael [7] who recommended a two-step procedure in this situation: Decouple breakdown and working periods, apply any standard algorithm to the working period, and paste together the results. In a second step we therefore modify the simple algorithm to overcome this drawback. It turns out that the modified version performs well even in situations with high variability in the system.

The message of the paper therefore is: Although there exists in the computer science literature a variety of general purpose algorithms for performance evaluation of complex networks, it is often advisable to look for special purpose algorithms which are adapted to the special problem dealt with. This recommendation surely applies when the machines to buy or to construct are of very high value.

Some related work. An introduction into the field of shovel-truck type operations is given by Carmichael [7] with an emphasis on "How to apply queueing models". He discusses the whole range of problems arising with queueing network models in this application area and gives recommendations how to proceed in such studies. Especially, he discusses data sets from the literature. The cyclic queues which are in the focus of our paper are the starting point of his description under the heading "Reconciliation of theory and practice". A more detailed description of closed queueing network models applicable in shovel-truck systems, especially of generalized Gordon–Newell networks and their algorithmic evaluation is given by Kappas and Yegulalp [8].

Ta, Ingolfsson, and Doucette [9] develop a linear integer program to optimize the number of trucks in a multi-shovel system with prescribed number of shovels. To determine the idle probabilities of the shovels they use simplified finite source queueing models. Zhang and Wang [10] consider a cyclic shovel-truck system of four stations: Loading, travelling loaded, unloading, travelling back empty, where the unloading station is given special attention. By simulation they confirm that the complexity of this station can be reduced to a single queue, which allows to apply general purpose algorithms from the literature to determine the system's capacity. A similar but different reduction of complexity for the four-station system was proposed in [11].

For modelling, analysis, and calculations in shovel-truck systems we refer to the books of Carmichael [12] and Czaplicki [13]. For details on closed two-station tandem queues we refer to Stoyan [14] and Daduna [15]. For the general performance analysis we refer to [5] and [6].

Carmichael [7] mentioned that this model with deterministic service and travel times was already used by Boyse and Warn [16] as a simple approach to evaluate computing systems using a two-stage cyclic queue. Clearly, such approximations

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