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A computational intelligence approach to improve the efficiency of repair services in the smart grid context☆

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ABSTRACT

In a smart grid context, self-healing is the capability of the system to perform fault location, fault isolation and service restoration in a fully automated process. Self-healing reduces the outage duration and can help improve the efficiency of the crews that must be dispatched in an emergency situation to repair the system and return it to its normal state. This work proposes an iterated local search algorithm to solve the Service Dispatch Problem (SDP) for assignment, scheduling and dispatching of those working crews to attend to emergency and regular orders. The main contribution involves simultaneously considering the working hour constraints related to the crews and the minimization of latency for both regular (*off-line* version) and emergency orders (*on-line* version). The computational results obtained from a test set of ten actual data instances of the problem highlight the effectiveness of the proposed algorithm when addressing the SDP.

1. Introduction

The power grid is evolving towards a smart grid (SG) [1]. On the supply side, electric utilities are increasingly adding new technologies for grid monitoring and automation, such as smart meters, remotely controlled switches (RCS), and intelligent electronic devices, alongside the deployment of an information and communication technology infrastructure. On the demand side, consumers are increasingly adopting distributed generation and engaging in demand-side management programs. Ultimately, the grid will be able to generate and deliver energy with high efficiency, safety, quality, availability and reliability. It will provide reduced costs of management and operation for the utilities and lower electricity rates for consumers. Last but not least, the SG will be resilient and able to self-heal after disturbances.

Indeed, self-healing is one of the most important features of the SG, as it allows the greater reliability and quality of the power supply. Therefore, the grid must be able to quickly locate and isolate the faulty section of the network and restore the energy supply to the affected consumers by rerouting power around the faulted section through RCSs. Furthermore, it should be able to ensure that as many customers as possible have access to the power supply while the faulted sections are repaired by repair crews [2]. In this context, at least two main classes of problems arise. One class is related to the problem of fault location, isolation and service restoration (FLISR); this problem should be computationally solved as fast as possible, preferably without human intervention, and using advanced distribution automation to reduce the duration of the interruption [3]. Another class is related to the repair problem,

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which comprises the assignment, scheduling and routing of repair crews and vehicles to the repair sites [4]. In this class of problem, the goal is to reduce the cost and repair latency of bringing the system to its normal state.

This paper focuses on the latter class of problems: managing a set of repair crews (or vehicles) to attend a set of repair services (or demands), here called service orders. The Travelling Repairman Problem (TRP) [5] is the most closely related combinatorial optimization problem in the context of service attendance addressed in this work, and it is called the Service Dispatch Problem (SDP). Its definition states that, assuming only one delivery repairman, the objective is to find a route that includes all repair service points (or demands) in such a way that the total waiting time for all of these points is minimized. However, because more than one repairman is generally required, a direct generalization of the TRP is adopted: the multiple travelling repairman problem (MTRP) [6], involving k identical vehicles or repair crews.

It is assumed that the MTRP is insufficient to address the SDP considered in this work because there are additional features to incorporate. The first feature refers to the time limit constraints related to crew's working hours; these constraints were recently addressed by Luo et al. [7], but there is no limit on the number of repair crews available, and their corresponding route time is assumed to be identical for all of them. In the problem addressed in this work, not only is the number of crews constant, but the limit related to working hours may vary from crew to crew. This may lead to a scenario in which not all services are included in the route, distinguishing another variant to be aggregated from the MTRP: the MTRP with profits [8].

Finally, two other features must still be aggregated: the service time for each order and the dynamic nature of the problem. Regarding the time of service, the orders require a certain execution time that is different for each of them. Regarding the dynamic aspect, this is the definitive and most important characteristic of the problem throughout a planning day: the planned route at the beginning of the day is systematically changed with the arrival of emergency services unknown a priori.

The main contribution refers to an SDP mathematical formulation, formally presented in Section 3, to develop an heuristic algorithm based on the metaheuristic *Iterated Local Search* (ILS) (described in Section 4) for sub-optimally solving the SDP. Computational results (Section 5) obtained by simulation for a test set of ten actual data instances report promising directions and the effectiveness of the algorithm proposed when solving the modified SDP. Final remarks and conclusions are presented in Section 6.

2. Literature review

Since the work of Weintraub et al. [9], which introduced the basic definitions of SDP, several approaches have been proposed, with an emphasis on classical optimization problems (TRP and its variants). However, the emphasis on the relationship between the SDP and TRP must be further reinforced when observing the central aspect of the problem: nodes in the SDP herein considered involve critical services that require the minimum waiting time.

Perrier et al. [4] introduced the diversity of work related to routing, scheduling and designation, with emphasis on the electrical sector. Most of these approaches are related more specifically to scheduling and designation [10], and only recently a work related to the classic related problem (TRP) introduced one of the most important characteristics of SDP: multiple crews [7]. Martin and Salavatipour [11] presented an approximate algorithm for the MTRP that considers identical vehicles, but it was still far from the premise of the SDP that requires a determined number of crews that may have different workday hours.

The premise of considering the MTRP with non-identical vehicles follows another characteristic that highlights another variant of the TRP that must be included to address the SDP: the presence of route time restrictions; i.e., all demand points are not visited on the planned route. This variant is known as TRP with profits and was addressed by Dewilde et al. [8] and, more recently, by Avci and Avci [12]. The contribution of Luo et al. [7] corresponds to the approach closest to the SDP, in which a Branch-and-price-and-cut algorithm to solve the MTRP with the inclusion of route time constraints for the crews is proposed. There are, however, two more obvious limitations: (i) all crews depart from only one depot, and (ii) the vehicles are identical.

Because there may exist random requests related to emergency orders in the SDP considered in this work, the dynamic characteristic first defined by Psaraftis [13], *the dynamic vehicle routing problem*, and recently surveyed by Pillac et al. [14] is considered. The work of Larsen et al. [15] is particularly relevant, as they note that there may be a nature that is not fully but partially dynamic with regard to the SDP. Following the review of the state-of-the-art solutions for these problems by Psaraftis et al. [16], the MTRP must consider the following additional characteristics: maximum route times, according to the crew's workday hours; multi-depot because each crew might have a distinct starting point; and service times in the nodes [17]. Moreover, considering the dynamic MTRP as the SDP assumed, this work deviates from the work of Souyris et al. [17] because a set of existing routes corresponds to the planning journey that will be modified by attending to a set of emergency orders.

After describing the literature review related to the problem (SDP) herein addressed, the corresponding solution approaches that have already been proposed are defined. Among the many theoretical contributions [11], as the state of the art, that are used to solve some TRP variations, common real-world applications of SDP generally involve instances of hundreds of nodes and suggest that heuristic approaches should have acceptable response times. Of the heuristic methods, supervised procedures, particularly metaheuristic ones, are competitive solutions for optimization problems and can be used in a wide range of applications [18]. The metaheuristic *Iterated Local Search* (ILS) [19] has been successfully applied to solve optimization problems, such as the Minimum Latency Problem [20] and the vehicle routing problem [21].

3. Problem statement

The SDP [9] occurs on each of the 365 days of the year, whenever there is a set of pending work orders and a set of working crews. Moreover, the work orders are given in the form of a prioritized queue, where orders have highly different service times and a high