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Solving a dynamic facility location problem with partial closing and reopening

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ABSTRACT

Motivated by an industrial application, we consider a recently introduced multi-period facility location problem with multiple commodities and multiple capacity levels. The problem allows for the relocation of facilities, as well as for the temporary closing of parts of the facilities, while other parts remain open. In addition, it uses particular capacity constraints that involve integer rounding of the allocated demands. In this paper, we propose a strong formulation for the problem, as well as a hybrid heuristic that first applies Lagrangian relaxation and then constructs a restricted mixed-integer programming model based on the previously obtained Lagrangian solutions. Computational results for large-scale instances emphasize the usefulness of the heuristic in practice. While general-purpose mixed-integer programming solvers do not find feasible solutions for about half of the instances, the heuristic consistently provides high-quality solutions in short computing times, as well as tight bounds on their optimality.

1. Introduction

Classical facility location aims at striking a balance between facility construction costs and transportation costs to satisfy customer demands. Operations research practitioners therefore contributed with a considerable variety of extensions to classical models to represent real world applications in a more realistic manner, involving the location of hospitals [31], telecommunication hubs [8], schools [1], manufacturing and distributing systems [27], and many others. The dynamic adjustment of the capacities over a planning horizon has often been a central issue. Problem extensions have been proposed to allow for the expansion and the reduction of capacity along time [23,1], temporary facility closing [8,10] and the relocation of capacities from one location to another [25]. Other important extensions acknowledged uncertainty in the customer demands [28] or the production capacities themselves (for references, see, e.g., [30]). Given the difficulty to solve those problems for real world sized instances, many solution algorithms have been suggested. Exact methods have been proposed for classical variants [35,15], whereas heuristics have proved to be effective for more complex problem variants. Due to the complicated structure of the latter, only a few works have applied methods that provide a bound on the solution quality, such as Benders decomposition and Lagrangian relaxation [10,20]. More complex problem variants have therefore been solved by methods such as sophisticated local search [22,26], which, by themselves, do not allow for an assessment of the solution quality.

In this paper, we consider a multi-period facility location problem with multiple commodities and multiple capacity levels that has recently been introduced and applied in the forestry sector by Jena et al. [17]. In the application considered by the authors, a logging company must locate camps to host its workers. The problem involves several different ways to adjust capacity, namely, the expansion of capacity, the temporary closing of parts of the facility and the relocation of facilities from one location to another. Many of these features have already been discussed in early literature. The first multi-period models include those by Ballou [2] and Wesolowsky [36]. Multiple commodities have been considered by authors such as Geoffrin [14] and Warszawski [34]. Modular capacity levels have often been treated by offering a choice of facility size [21,29,9,16], whereas capacity expansion has been discussed in detail by Luss [23] and has been found to be a crucial feature in many applications [1,7,25]. Wesolowsky and Truscott [37] have been among the first to consider simple relocation of facilities, followed by several others [27,6,25]. While the temporary closing of entire facilities has been modeled in several studies [33,8,7,10], the problem introduced by Jena et al. [17] was the first to consider the partial closing and reopening of facilities along time. The authors propose a flow based formulation that uses a network structure for each facility location to manage the amount of available capacity and the amount of temporarily closed

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capacity of the facility. An integer flow, representing the number of open and closed capacity levels, allows for the closing of open capacity and the reopening of closed capacity. Another feature of the problem is the use of the so-called round-up capacity (RUC) constraints, which imply integer rounding of the total demand for each commodity allocated to the same facility. While this characteristic may correspond to the practice in many industries, to the best of our knowledge, the authors were the first to explicitly model this type of capacity constraints. Modeling the problem's features in detail results in complex models that raise questions of tractability. The problems solved by Jena et al. [17] were therefore of rather small size.

Contributions: In this paper, the above problem, subsequently referred to as the *Dynamic Facility Location Problem with Relocation and Partial Facility Closing (DFLP_RPC)* with RUC constraints, is revisited. A new formulation and a heuristic solution method are proposed to solve instances that are approximately 20 times larger in terms of facility locations and customers. We summarize our contributions as follows. First, a new mixed-integer programming (MIP) formulation for the DFLP_RPC with RUC constraints is introduced, based on the modeling technique proposed by Jena et al. [18]. While the latter considers rather simple variants of dynamic facility location problems, the formulation presented here accounts for additional features, namely the partial closing and reopening of facilities, the relocation of facilities and the round-up capacity (RUC) constraints. The new formulation has several advantages when compared to the formulation proposed by Jena et al. [17]. It yields integrality gaps that are, on average, more than 29 times smaller. Furthermore, it enables a state-of-the-art MIP solver to find feasible solutions for significantly more instances and to achieve a higher solution quality. The new formulation also allows for a more detailed representation of the cost structure. Second, we propose a Lagrangian based heuristic, capable to address large scale instances of the DFLP_RPC with RUC constraints. The heuristic consists of two optimization stages. In the first stage, Lagrangian relaxation is applied to provide lower and upper bounds for the problem. Then, a restricted MIP model, based on the Lagrangian solutions, is solved to improve the final solution quality. The heuristic substantially extends those proposed by Jena et al. [19] and accounts for the additional problem features, i.e., the partial closing and reopening of facilities, the relocation of facilities, and the RUC constraints. The technical challenges induced by these new features impact the algorithm on all levels: the set of relaxed constraints, the dynamic programming algorithm to solve the Lagrangian subproblems, the generation of primal feasible solutions, and the feeding strategy for the restricted MIP. Computational results have shown that the combination of the new formulation and the Lagrangian heuristic is quite powerful. The proposed heuristics are capable of finding high quality solutions in short computing times, even for large-scale instances for which a state-of-the-art MIP solver does not find feasible solutions. Furthermore, due to the strength of the proposed formulation, the heuristics provide significant bounds on the quality of the obtained solutions.

Outline: The remainder of the paper is organized as follows. Section 2 defines the problem and its application in forestry. Then, Section 3 introduces the new formulation for the DFLP_RPC with RUC constraints. The two-stage Lagrangian heuristic is presented in Section 4. Computational experiments for the problem, as well as for simplified problem variants without relocation and without RUC constraints, are presented in Section 5: the linear programming (LP) relaxation and the integrality gaps of the problems are analyzed; furthermore, the quality of the solutions for the industrial problem provided by a general-purpose MIP solver and the proposed heuristics are compared. Finally, conclusions are drawn in Section 6.

2. Problem description

We consider the problem introduced by Jena et al. [17], which extends the Capacitated Facility Location Problem in several aspects: multiple time periods, multiple (modular) capacity levels and multiple commodity types. Given a set of customers with independent demands for each commodity and time period, the objective is to find the optimal locations and opening schedules for facilities that provide sufficient capacity to satisfy the customer demands at minimal costs. New facilities may be constructed and existing facilities may expand their capacity at any time period. Since a facility may not always require its entire capacity, parts of the facility may be temporarily closed, while other parts remain open.

Given that the temporary closing and reopening of capacity is usually much cheaper than the complete shut-down and construction of a facility, this feature may result in a very dynamic opening schedule of the facilities. Throughout this paper, we will denote the capacity that is available for use as the *open* capacity. In contrast, we denote the capacity that is temporarily not available as the *closed* capacity. Closed capacity can be reopened at a later moment. Finally, the *existing* capacity is defined as the sum of the open and the closed capacity. Facilities may be relocated from one location to another, assuming: (1) a facility can only be relocated as a whole, not partially; (2) before it is relocated, the entire capacity of a facility has to be closed; (3) facilities cannot be merged at the same location.

In contrast to classical facility location models, the problem considered here involves particular capacity constraints, the above mentioned round-up capacity (RUC) constraints. These constraints require that, even though facilities may be able to provide the exact level of capacity required, they need to reserve production capacity in multiples of a certain size. This involves rounding the demands for each commodity according to the lot sizes to compute the total capacity necessary at the facility. The following example illustrates these constraints. In a given time period, a set of customers have been allocated to obtain a total of 287 units of commodity A and 113 units of commodity B from a certain facility. Let us assume that this facility needs to reserve blocks of size 100 for the production of commodity A and blocks of size 150 for the production of a commodity B. Even though the facility may produce the exact amount required by the customers, it needs to ensure a total capacity of 300 units, i.e., three blocks, for commodity A and 150 units, i.e., one block, for commodity B.

Application in industry: The DFLP_RPC with RUC constraints was motivated by an industrial application in the forestry sector introduced by Jena et al. [17], where a logging company needs to locate camps to host its workers. Facilities represent logging camps, while customers represent logging regions that specify a total demand for two different commodities: the workforce for wood logging and the workforce for the construction and maintenance of access roads. Demands are specified over a time horizon of five years, each year divided into a summer and a winter season. Logging camps are composed by trailers and therefore have a very flexible structure. The capacity level of a facility thus represents the number of trailers at the camp. The hosting capacity of a logging camp can easily be expanded by adding new trailers. Some trailers may be closed, while others remain open. Trailers are only available for use when they are open. The total number of trailers of a camp, i.e., the sum of open and closed trailers, is also referred to as the number of existing trailers. Demands are specified as the average number of crews working throughout the entire season. It is likely that a crew will only work a part of the season in a given region, which leads to a fractional demand. Given that crews always work together, the logging camp must ensure sufficient hosting capacity for the entire crew. The RUC constraints therefore ensure that capacity is modeled in a