Optimizing the multi-phase deployment of a district cooling system by mixed-integer linear programming

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A district cooling system (DCS) is a centralized cooling supply system providing air conditioning to a set of buildings located in the same district. In a DCS, chillers convert electricity to cooling power which is distributed in the form of cold water through an underground pipe network to the buildings in the district. In the present work, we consider two types of chillers. The first one is standard chillers which only produce cooling power to satisfy the instantaneous demand of the customers. The second one corresponds to ice chillers which have two distinct operating modes. They either produce cooling power, but usually with a lower efficiency than the one of a standard chiller, or they produce ice. This ice can be stored for a few hours in an ice storage tank and be melted afterwards to provide cooling power.

Designing a DCS involves choosing the type and number of chillers to be installed as well as the ice storage capacity. These decisions should take into account not only the construction costs, but also the operation costs of the system during its whole lifetime. Computing these operation costs is a challenging problem. Namely, the demand for cooling power is highly variable and features a daily, weekly and yearly seasonality together with random variations. Moreover, due to technical reasons owing to the chillers, these operation costs are not at all proportional to the produced cooling power. In order to accurately compute them, a detailed schedule describing, on a hourly basis, the on/off status and the load allocation of each chiller should be built for an horizon spanning a whole year. Furthermore, the deployment of a district cooling system is usually not a one-shot decision but rather a process in which investment decisions are made step by step, following the development of the district over the years. This implies that a multi-year strategic deployment plan should be built.

This optimization problem can be formulated as a mixed-integer program. However, its resolution poses several difficulties. The first one comes from the non-linearity of the chillers' performance curves. These performance curves give, for each chiller, the amount of electricity consumed as a function of the amount of produced cooling power and thus play a key role in the estimation of the system operation costs. Second, the need to simultaneously build a multi-year phasing plan and a detailed operational schedule for each day of the planning horizon leads to the formulation of a huge mathematical program, which cannot be solved directly by current mathematical programming solvers. Finally, the use of classical decomposition methods, such as the Benders' decomposition approach, is not straightforward as it would imply sub-problems involving binary and/or integer decision variables. The mixed-integer program modeling the problem is thus computationally intractable as such.

In the present work, we propose a solution approach for the optimal design, over a multi-phase investment horizon, of a local district cooling system in which intra-day ice storage is allowed. This approach relies on three key elements.

First, we seek to reduce the size of the initial optimization problem. We thus consider a deployment plan involving a limited number of phases, some of which spanning several years. Moreover, we use the clustering approach described in [1] to select a small set of typical days to represent with the smallest possible loss of accuracy the various conditions under which the system will be operated.

Second, we build a piecewise linear approximation of the performance curves of each chiller. Moreover, we propose a way to exploit the convexity of these curves to reduce the size of the formulation of the operation scheduling sub-problems and limit numerical difficulties coming from symmetries in optimal solutions. This results in the formulation of a large-size mixed-integer linear program (MILP).

Thirdly, we develop an exact solution algorithm based on the hierarchical decomposition method recently proposed in [2] to solve this MILP. This methods relies on a customized Branch & Cut algorithm exploiting the hierarchical relationship between the design and operation decision variables of the mathematical program. The upper level problem corresponds to the initial optimization problem in which all operational integer and binary variables are kept but relaxed to be continuous. This relaxation of the initial problem is solved by a standard Branch & Cut algorithm. Each time a potential incumbent design solution is found during this tree search, the corresponding values of the design variables are used as input data to solve a series of independent scheduling sub-problems (one for each typical day and each investment phase). This gives an accurate estimation of the feasibility and value of the potential design solution. If this solution is found to be feasible and better than the current incumbent solution, it is accepted as the new incumbent solution. Otherwise, it is rejected. When all the branches are searched in the upper level Branch & Bound search tree, the current incumbent solution gives the optimal solution of the original problem.

We provide preliminary computational results based on a real-life case study in China. These results show that the customized algorithm significantly outperforms the generic Branch & Cut algorithm embedded in CPLEX solver in terms of computation time.

References

[1] Zatti M, Gabba M, Freschini M, et al. k-MILP: A novel clustering approach to select typical and extreme days for multi-energy systems design optimization[J]. *Energy*, 2019, 181: 1051-1063.

[2] Yokoyama R, Shinano Y, Taniguchi S, et al. Optimization of energy supply systems by MILP branch and bound method in consideration of hierarchical relationship between design and operation[J]. *Energy conversion and management*, 2015, 92: 92-104.