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Design optimization of air distribution systems in non-residential buildings

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ABSTRACT

Centralized air distribution systems in non-residential buildings are characterized by an extensive air distribution network, that has to be built in a building environment with finite degrees of freedom. The ductwork layout, i.e., the network structure of the ducts, as well as the number and location of the fans, has a large impact on the total cost and performance of the air distribution system. Nevertheless, existing air distribution system design methods are limited to the sizing of each duct (and fan) in the network. The layout itself is considered predetermined, and thus not explicitly taken into account for optimization. In this paper, we meet this shortcoming by presenting the air distribution network design optimization method, that is able to calculate the optimal air distribution system configuration, i.e., the optimal layout and duct and fan sizes, while minimizing the total cost of the air distribution system. A multi-start local search algorithm is developed, consisting of a constructive and a local search phase. In the first phase, multiple air distribution system configurations are generated, and evaluated for feasibility. In the local search phase, all feasible solutions are further optimized in terms of material costs by decreasing and increasing the duct diameters following the steepest descent/mildest ascent approach. An application of the algorithm on a realistic test case demonstrates its usefulness in practice.

1. Introduction

Reducing the energy consumption in buildings, and expanding renewable production were, are, and will continue to be key objectives of European policies to achieve sustainability and a competitive low-carbon economy [1]. The global contribution of buildings towards the energy consumption in developed countries is significant [2], and thus one of the goals is to increase the energy efficiency of building services. Among these building services, HVAC systems, and more specifically air distribution systems, not only have a substantial share in the buildings' energy consumption, but are also very cost expensive [3,4]. By ensuring the high quality of the design of air distribution systems or networks, both material and energy costs can be reduced notably. Meanwhile, the energy efficiency, effectiveness, and comfort of the air distribution system will only increase. This paper focuses on the design process, by developing an optimization method for the design of air distribution systems in non-residential buildings.

Air distribution systems in non-residential buildings are often centralized systems with one or more resource nodes, i.e., air handling units or fans. Through extensive tree-networks of supply air ducts, conditioned air is distributed out through the building to multiple demand nodes, i.e., terminal units. Generally, the air flows back to the air handling unit(s) to be reconditioned or exhausted from the building by the extraction and exhaust ductwork respectively. The energy required for the air distribution through the ductwork, and the compensation of all pressure losses caused by, among other things, fittings, dampers, diffusers, and air grilles, is delivered by one or more fans.

During the design phase of air distribution systems, the design engineer is faced with many decisions that affect the (conflicting) objectives of the design problem, such as the maximization of the performance and the minimization of the different costs (e.g., material, installation, and energy costs). These decisions are mainly related to the following two successive steps in the design process, i.e., the determination of the ductwork layout, and the dimensioning of the air distribution system. When all demand nodes with corresponding air flow rates are indicated on a building's floor plan, the ductwork layout, i.e., the location of each duct and fan in the building is determined. Once the route has been drawn that

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the branched ductwork follows starting from the fan(s) to the demand nodes, all duct and fan sizes are calculated. In practice, these two steps are often repeated several times.

1.1. State of the art

Numerous research papers have been dedicated to the optimization of air distribution systems, with the focus varying from research to research. Several papers focused, for example, on the optimization of the fittings in the air distribution system [5], while other papers studied the control strategies [6], the optimal airflow and the geometry of the ductwork [7], or the duct and fan sizing [8–11].

This research paper is an extension of the latter research field. Jorens et al. [12] gave a critical review of several existing design (optimization) methods to dimension the ducts (and fans) in the air distribution system (e.g. the static regain method, equal friction method, T-method), and identified two main shortcomings. First, previous methods only focus on the second phase of the design process, i.e., they only determine the size of each duct and/or fan in the system and consider the layout to be given. The layout itself is determined using rules of thumbs, which results in designs that are workable, but not necessarily optimal from a technical or economical point of view. Second, most methods have solely been tested on small air distribution systems such as the ASHRAE benchmark network [8], and thus no general conclusions can be drawn on their performance on large realistic air distribution networks in non-residential buildings (e.g., office and school buildings). As a result, air distribution systems are generally largely designed manually, and their performance relies on the knowledge and experience of the engineer in charge of the design. Evidently, the field of air distribution system design would benefit from models and methods that allow for more advanced optimization and automation of the design process.

1.2. Optimization of large air distribution systems

Typical for the design of large air distribution systems in non-residential buildings, is that the designer is faced with many constraints and requirements (e.g., limitations on space, noise level, pressure losses, duct sizes) [13]. Asiedu [3,14] states that metaheuristic techniques such as evolutionary metaheuristics are needed to tackle large complex air distribution network designs. Sörensen and Glover [15] define metaheuristics as “high-level, problem-independent algorithmic frameworks that provide a set of guidelines or strategies to develop heuristic optimization algorithms”. They don’t guarantee to find the optimal solution, but are able to find solutions that are ‘good enough’ in an ‘acceptable’ computing time. Three main metaheuristic strategies can be distinguished: local search, constructive, and population-based strategies. With a local search approach a new solution is obtained by iteratively making small changes to a current solution. A constructive heuristic, on the other hand, starts with an empty solution, and iteratively extends the current solution until a complete solution is obtained. When solutions are repeatedly combined into new ones, a population-based strategy is used. (Meta)heuristics have proven their usefulness in numerous complex related engineering fields, such as water distribution network design optimization [16,17], utility network design [18], and HVAC system energy optimization [19].

1.3. Contribution

This paper aims to develop an optimization method, which we call the air distribution network design (ADND) optimization method, to support the design engineer in optimizing the design of air distribution systems in non-residential buildings. Contrary to existing methods, the generation of the layout and the duct and fan sizing are treated as interrelated decisions, and are both tackled in the optimization method. Network design decisions, such as the route that has to be followed from the fan to the demand nodes, and the optimal type of ducts that have to be selected to connect the supply (i.e., fan(s)), demand, and junction nodes in the network, are supported by the ADND optimization method. One of the main advantages of the ADND optimization method, is that it is able to quickly generate several alternative feasible solutions. This is a major advantage over existing methods that are still completely dependent on the brainpower of the engineer in charge to determine the layout, especially when the air distribution systems increase in size. By integrating the layout into the optimization method, the efficiency of the network design decisions, and thus, the quality of the solutions will improve substantially. Moreover, valuable engineering time and costs are saved. Second, our method allows the design engineer to quickly respond to external changes during the design phase, e.g., modified air flow rates in one or more rooms, adapted dimensions of the false ceiling, and changed locations of the support beams in the building. These changes have a significant influence on the air distribution system’s configuration. Currently existing methods fall short here. The next section gives insight into the ADND optimization problem, while the development of an algorithm to solve this ADND problem is discussed in Section 3. Section 4 covers the application of the algorithm on a realistic test case. Conclusions and pointers for future research are addressed in the last section.

2. Air distribution system design optimization

In this paper, we formulate the ADND optimization problem, in which both the layout decisions and the duct and fan type decisions are taken simultaneously. The ADND optimization problem is formulated as a non-linear combinatorial optimization problem. Although real-life air distribution systems should be evaluated on multiple criteria (installation costs, life-cycle costs, energy consumption, noise levels, ...), minimization of the material costs is generally seen as an important objective in practice. We therefore define the ADND optimization problem as a single-objective optimization problem. Criteria such as comfort and energy use are being taken into account indirectly by establishing constraints that the air distribution system must meet.

The ADND problem was introduced for the first time by Jorens et al.[12], but is extended in this paper by adding several sets of additional constraints, e.g., the maximum pressure constraints and telescopic constraints. All constraints, described in Section 2.2, are integrated in the ADND optimization method, and render the solutions generated by our algorithm more realistic (Section 3).

2.1. Problem formulation: objective function

To formulate the ADND optimization problem as a mathematical model, the building is represented as a graph $G(N, E)$ with E being the set of edges representing (potential) air ducts and N the set of nodes representing (potential) supply nodes (fans), demand nodes (terminal units), and junctions. All possible fan locations, and fan types, as well as all possible duct types between any pair of nodes are assumed to be predetermined. The recommended airflow rate at each terminal unit, and thus the total airflow for the complete air distribution system is also assumed to be known. All this information can be obtained from building plans and is given as input to the optimization algorithm. Fig. 1 gives an example of a representation as a graph of one floor in a multi-floor office building. It is clear that this is not yet a valid air distribution network or system, since such a network consists only of one or more trees