Design Optimization of Air Distribution Systems in Non-Residential Buildings

Sandy Jorens[1*], Ivan Verhaert[1], Kenneth Sörensen[2]

[1]University of Antwerp, Energy and Materials in Infrastructure and Buildings (EMIB – HVAC), 2020 Antwerp, Belgium
[2]University of Antwerp, Operations Research Group (ANT/OR), 2000 Antwerp, Belgium

ABSTRACT

In most heating, ventilation and air conditioning systems, the ductwork layout, i.e., the network structure of the ducts, as well as the number and location of the fans, is an important determinant of the installation's cost and performance. The network layout is especially important in large, non-residential buildings with an extensive air distribution network. Nevertheless, existing duct design methods do not explicitly take the layout into account. On the contrary, most methods assume the layout of the air distribution system to be predetermined and focus solely on the sizing of each fan and duct in the network. In this paper, previous research is extended by presenting a novel problem formulation that integrates the layout decisions into the optimization problem. In this problem, which we call the air distribution network design optimization problem, the optimal ductwork layout is determined jointly with the duct and fan sizes, thereby minimizing the total cost of the system. This novel combinatorial optimization problem is characterized by discrete decision variables, and non-linear constraints and can best be approached by metaheuristic optimization techniques. This paper focuses on the development of a heuristic optimization algorithm, i.e. a multi-start local search algorithm, that is able to solve the air distribution network design optimization problem efficiently. An application of the algorithm on a realistic test case demonstrates its usefulness in practice.

KEY WORDS: air distribution system design optimization, ductwork layout, heuristic optimization algorithm

1. INTRODUCTION

One of the most energy-consuming and cost expensive parts of a heating, ventilation and air conditioning (HVAC) system is the air distribution system [1, 2]. Both the energy and material costs can be reduced significantly if air distribution systems or networks are designed properly. The quality of their design largely determines the effectiveness, energy-efficiency and comfort of a building's HVAC system. Centralized air distribution systems in non-residential buildings can be seen as large tree-networks of supply air ducts that convey conditioned air from one or more resource nodes, e.g., air handling units or fans, out through the building to multiple demand nodes (terminal units). Usually, the air is returned back to the air handling unit to be conditioned again or exhausted from the building by the extraction and exhaust air ductwork respectively. It is the design engineer's responsibility to design the air distribution system in such a way that each demand point is provided with the required airflow at adequate pressure. The energy needed to distribute the air and overcome all the pressure losses of the various components in the network (e.g., fittings, silencers, dampers), is delivered by one or more fans. Starting from a floor plan where all terminal units in the building with corresponding air flow rates are indicated, the design process of air distribution systems can generally be subdivided in three different phases. First, the ductwork layout needs to be determined, i.e., the route that the branched ductwork follows starting from the resource node (fan) to the demand nodes (terminal units) in the building. Second, all duct types (i.e., size and material) and fan(s) are

*Corresponding Author: sandy.jorens@uantwerpen.be

selected. Last, dampers for the different branches in the network are calculated to balance the system and ensure that every demand point receives the correct airflow.

1.2. State of the art

Numerous papers have been dedicated to the design of air distribution systems or networks and several design (optimization) methods have been developed [3, 4, 5, 6], e.g. the static regain method, equal friction method, T-method, … Jorens et al. [7] give a critical review of the state-of-the-art in air distribution system design and identify 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 [3], 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. Clearly, the field of air distribution system design would benefit from models and methods that allow more advanced automation and optimization of the design process.

1.2 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, 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, since they do not take the layout into account. 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 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 consumption are being taken into account indirectly by establishing constraints that the air distribution system must meet.

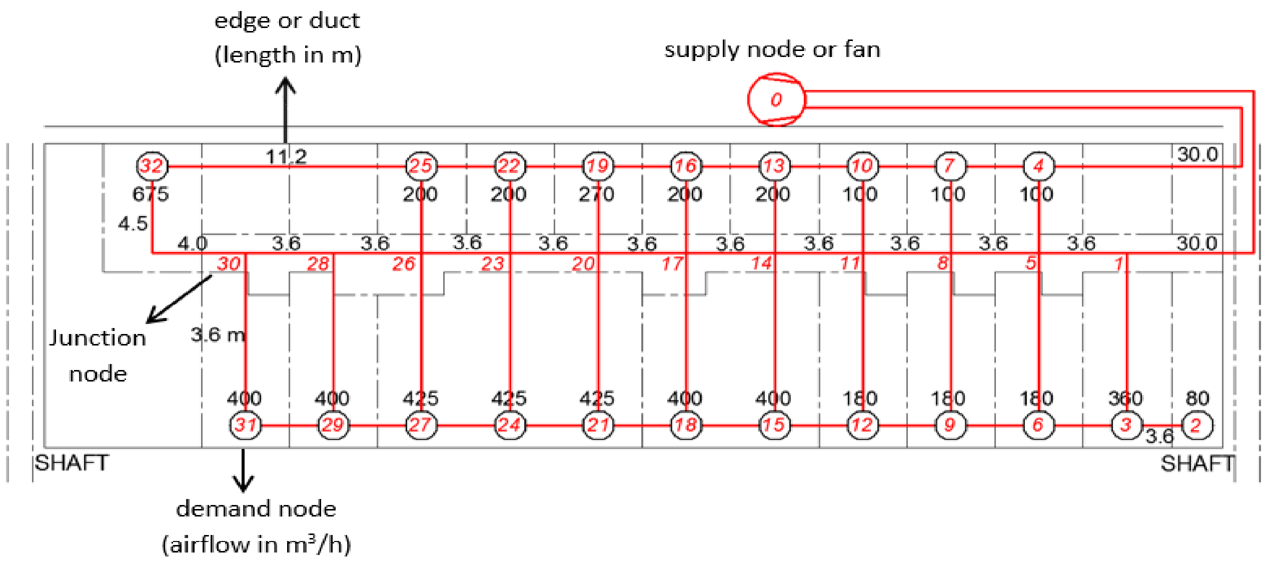

Fig. 1: representation of one floor in an office building as a graph G with 51 edges and 33 nodes, from which 1 supply node (i.e., a fan), 11 junction nodes, and 21 demand nodes.

To formulate the ADND problem as a mathematical model, the building is represented as a graph G(N, E) with E being the set of edges that represent (potential) ducts and N the set of nodes representing junctions, points of demand (terminal units), and potential points of supply (fans). The possible location(s) of the fan(s), as well as the possible fan types, and all possible types of ducts between any pair of nodes are assumed to be known. The required airflow rate at each terminal unit, and thus the total airflow for the entire air distribution system is also assumed to be predetermined. All this information can be obtained from building plans and is given as input to the optimization algorithm. Figure 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. The output of the algorithm is either a tree with minimum cost that connects all demand nodes to the fan and satisfies all constraints, or multiple subtrees where each subtree has its own fan. Four outcomes of the algorithm are represented as an example in figure 3. The objective function is defined as the sum of the duct costs and the fan costs:

$$\text{Minimize cost} = \sum_{d \in D} \sum_{t \in T} x_{td} C_{td} L_d + \sum_{f \in F} \sum_{s \in S} x_{sf} C_{sf} \qquad (1)$$

In the equation x_{td} is a binary decision variable that determines whether duct d is selected to be of type t (x_{td} = 1) or not (x_{td} = 0). The same applies to the fan selection, i.e., when a fan of size s is selected at location f, x_{sf} equals 1 and when a fan of size s is not selected, x_{sf} equals 0. The first term of equation 1 represents the cost of the ductwork, which depends on both the total length L_d of each duct d, the type t selected for duct d, and the cost per unit of length for a duct of type t. Each duct type has a different nominal duct size (chosen from a list of commercially available types T), resulting in a certain unit cost per meter C_{td} for circular ducts and a unit cost per square meter for rectangular ducts. The second term of the formula represents the material cost of the fans, where C_{sf} is the cost of a fan of type s. The type of a fan is amongst others determined by its size, fan performance or characteristic curves and its application field (centrifugal or axial fan).
Typical for the design of large air distribution systems in non-residential buildings, is that the designer is faced with many constraints and requirements. The constraints define the viability of the air distribution system design, and are listed below:

- *mass balance* - the mass conservation law states that the mass of air flowing into a node in the network per unit of time equals the mass of air flowing out of this node;

- *pressure balance* - the pressure balancing constraint requires that the total path pressure losses are the same for all duct paths in the network;
- *maximum pressure* - from an energetic point of view, the pressure loss of the critical path, i.e., the path with the highest pressure loss that determines the fan pressure, should be restricted;
- *air velocity* - limitations are set on the air velocity to reduce duct noise;
- *nominal duct sizes* - the set of commercially available duct sizes, to choose a duct from, is limited;
- *space limitations* - the maximum allowable duct diameter depends on the available building space;
- *telescopic constraint* - the diameter of the upstream duct must be greater than, or equal to the diameter of the downstream duct.

Except for the pressure balance constraint, all constraints are mandatory, unless otherwise required by the designer.

Since exact methods are subjected to a combinatorial explosion as the size of the problem increases, it can be posited that the ADND optimization problem is outside the realm of exact methods. Asiedu [1] states that metaheuristic techniques such as evolutionary metaheuristics are needed to tackle large complex air distribution network designs. Sörensen and Glover define metaheuristics as “high-level, problem-independent algorithmic frameworks that provide a set of guidelines or strategies to develop heuristic optimization algorithms” [8]. They don’t guarantee to find the optimal solution, but are able to find solutions that are ‘good enough’ in an ‘acceptable’ computing time. (Meta)heuristics have proven their usefulness in numerous complex related engineering fields, such as water distribution network design optimization [9, 10], and HVAC system energy optimization [11].

3. HEURISTIC OPTIMIZATION ALGORITHM

To solve the ADND optimization problem, we have opted for a multi-start local search strategy with two phases, a constructive and a local search phase. In the first phase a complete solution is constructed, while in the second phase the solution is improved by making iteratively small changes to the current solution, resulting in a local optimum. To be able to find the global optimum (i.e., the best possible solution to the optimization problem), and not being trapped in a local optimum, the search is restarted multiple times from a new, semi-random, solution. Specific for the ADND optimization problem, this means that in the construction phase a new network configuration (i.e., a new layout and duct and fan sizes), is constructed, after which its feasibility is evaluated. When feasible, small changes to the duct sizes are applied until a local optimum is reached. After restarting the whole procedure multiple times, the best overall solutions are selected. The algorithm is represented as a flowchart in figure 2, and all steps are discussed in detail in the next paragraphs for air distribution systems with one centralized fan. The programming language Python has been selected to implement the algorithm.

1. Input data - The input of the algorithm contains the data of all potential ducts that can be selected to be part of the final solution as well as the location of the fan that can be potentially installed (see figure 1). The input can be seen as an undirected weighted graph with the fan as root node and the ducts as weighted edges. Every duct is characterized by an initial and final node, and one or more weights. For now, two weights are assigned to each duct, i.e. a length and an average air velocity. Additionally, a list with all the demand nodes and corresponding air flow rates, and all the constraints, i.e., maximum allowable duct diameter, air duct velocity and fan pressure are given as well as input to the algorithm.

2. Layout generation - Each layout is a directed tree that connects the root node (i.e., the fan) to all the end nodes (i.e., demand nodes) through one or more junctions (i.e., nodes without a demand airflow rate). It’s important that every end node of the tree, i.e., a node with only incoming and no outgoing edges or ducts, is a demand node. Junctions can therefore never be end nodes. The generation of each directed tree or layout is largely randomized to allow for variation in the selected designs. With each layout generation, two lists are created, a node list and a duct list. The first list stores all nodes that are included in the current solution and the second list contains all edges or ducts. Initially the node list only contains the root node (i.e., the fan), and the

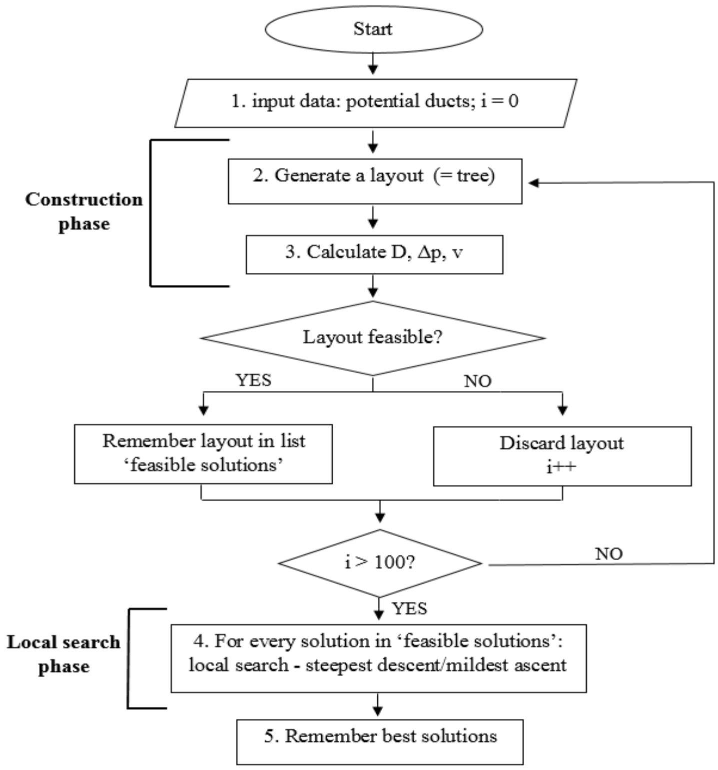

Fig. 2: flowchart of the ADND optimization algorithm

duct list is empty. The directed tree is then constructed duct by duct by repeating three sequential steps. First, one node is randomly selected from the node list as the initial node of a new duct. During the first iteration, this node is of course the root node, since this is the only node in the list. Second, one neighbor is randomly selected out of all the neighbors of the previous selected initial node. A node can only be defined as a neighbor of a certain node, if this node is connected with the other node through one edge or duct (e.g., node 1 and 6 are neighbors of node 3 in figure 1). The selected neighbor becomes the final node of the new constructed duct. To avoid loops in the layout, it is important to note that a neighbor can only be selected as a duct's final node, if it is not yet part of the node list. Third, the selected neighbor or final node is added to the node list and the duct is added to the duct list. These three steps are repeated until all the demand nodes are included in the node list, and thus in the tree.
Next, all end nodes of the tree are checked. If there exists an end node that is not a demand node, the associated duct will be deleted from the solution. This step is repeated until all the end nodes of the tree are demand nodes. Finally, all different paths in the tree are determined. A path is defined as a finite sequence of edges or ducts that connects the root node (i.e., the fan) with an end node of the tree. The number of paths equals the number of end nodes in the tree.

***3. Calculate diameters, pressures and velocities* -** Each time a layout is generated, the ducts' air flow rates, dimensions, air velocities and pressure drops are calculated, as well as the pressure drop over each path in the tree structure. When all constraints, defined in section 2, are fulfilled, the air distribution system configuration is considered feasible.

***4. Local search* -** Every feasible solution is subjected to a local search phase. In this phase, the duct diameters of each solution are further optimized in terms of cost. By iteratively making small changes or moves to the duct diameters, i.e., decrease or increase a duct diameter with one size, we aim to find a local optimum for every feasible solution. The steepest descent-mildest ascent approach is chosen as move strategy. This means that every move may result in a best possible improvement or a least possible deterioration of the objective function. Specifically for the ADND optimization problem, the largest duct diameters are decreased first one per one, since these adjustments improve the objective function the most. The cost savings resulting from a diameter decrease of a large duct with one size are much larger than when a small duct is decreased with one size. As soon as the pressure drop over each path in the solution equals or exceeds the maximum allowable pressure, the smallest diameters will be increased one per one, until the maximum pressure constraint is fulfilled for every path in the solution. When selecting ducts to decrease or increase, the telescopic constraints (see section 2) always has to be satisfied.

5. Solutions - The n best local optima are stored in a list. It is important that sufficient solutions are saved, so that there is enough variation in the air distribution layouts. The design engineer in charge has to make the trade-off between the investment costs and energy consumption.

4. TEST CASE

In this section, the ADND optimization algorithm is applied to one floor of a multi-floor office building. The floor is composed of a mixture of small and large offices, and meeting rooms, and requires a total air flow rate equal to 5900 m3/h. The location of all demand nodes, and the associated air flow rates (in m3/h) are indicated in figure 1.The fan is located in the technical room on the top floor of the building.

4.1 Input data

As stated in section 3, the following information is given as input to the optimization algorithm: the initial and final node, length (in m) and average velocity (in m/s) of each duct that can potentially be installed, the location of the supply node, potential junctions and demand nodes, and the air flow rates that are associated to the corresponding demand nodes (in m3/h). Figure 1 gives a graphic representation of the input data. An average velocity of 3 m/s, and a maximum velocity of 4 m/s is assumed for every duct, with exception of the two main ducts '0-1' and 0-4'. These two ducts have a maximum velocity of 5m/s. The maximum permitted pressure drop is set at 60 Pa, and the maximum diameter at 710 mm. For now, only circular ducts are considered. In practice, ducts of this size are rarely installed, instead rectangular ducts are used. Rectangular ducts score less in terms of energy and acoustic comfort, but take up less space.

4.2 Results

As an example, four different air distribution system configurations, generated with the ADND optimization algorithm, are graphically represented in figure 3. For each layout, all duct diameters are given (in mm), as well as the total cost of the ductwork (in euro), and the pressure drop over the critical path in the network (in Pa). The latter parameter determines the required fan power, and thus the energy consumption. The total ductwork cost was calculated using the price catalog of Lindab. From all solutions, layout 1 has come out as the best solution, i.e. the solution with the lowest material price, that fulfills all predetermined constraints described in section 4.1. The remaining three layouts were generated by adjusting the maximum pressure and maximum diameter constraints. This is to demonstrate that the ADND optimization algorithm is able to generate completely different air distribution system configurations depending on the designer or customer's requirements, and that the layout has a significant impact on the material price and energy consumption. Layout 1, for example, is the cheapest solution. However, it can be more beneficial to select a slightly more expensive layout, e.g. layout 2, which has a lower pressure drop over its critical path. From an energetic point of view, layout 4 scores the best out of the 4 selected layouts, but this solution may not outweigh the additional material costs, i.e., an extra 32.8 % compared to layout 1. Especially when we consider the entire office building instead of only one floor. The additional costs will increase tremendously in this case. It is up to the design engineer in charge to make the trade-off between the energy consumption and the material costs.

5. CONCLUSION AND FUTURE RESEARCH

The results displayed in figure 3 clearly show that the layout has a great influence on the air distribution system's cost and energy consumption. Nevertheless, the layout has not been taken into account in previous design methods for air distribution systems. Instead, all existing design methods start from a layout determined using rules of thumbs, and focused solely on the sizing of each duct and fan in the air distribution network. To meet this shortcoming, an ADND optimization algorithm is developed in this paper, that includes both the optimization of the layout, and the duct and fan sizing. In this research the ADND optimization problem is formulated as a single objective optimization problem, with the minimization of the material costs as the single objective function. The ADND optimization problem is characterized by discrete decision variables and numerous linear and non-linear constraints that must be satisfied. Therefore, heuristic techniques are used to solve this optimization problem. More specifically, a multi-start local search heuristic algorithm is implemented in this paper. As demonstrated in the test case (section 4), the ADND optimization algorithm is able to generate quickly numerous alternative air distribution system configurations for a building. It is up to the design engineer to select the configuration that fulfills his requirements most. He has to make a trade-off between the material and energy costs.

The main purpose of this paper was to lay the necessary groundwork for the development of the methodology to solve the ADND optimization problem. Of course, shortcomings can still be identified that need to be solved before the optimization algorithm can be applied in practice. For example, the installation and energy costs are not yet included in the objective function. The same applies to the fittings. These have not yet been taken into account, but will have an influence on the total cost price ,and the pressure loss of the critical path. These ,and other shortcomings can be solved by expanding our design method step by step. The ADND optimization algorithm, developed in this paper, can therefore serve as a good foundation for future research in the field of air distribution system design.

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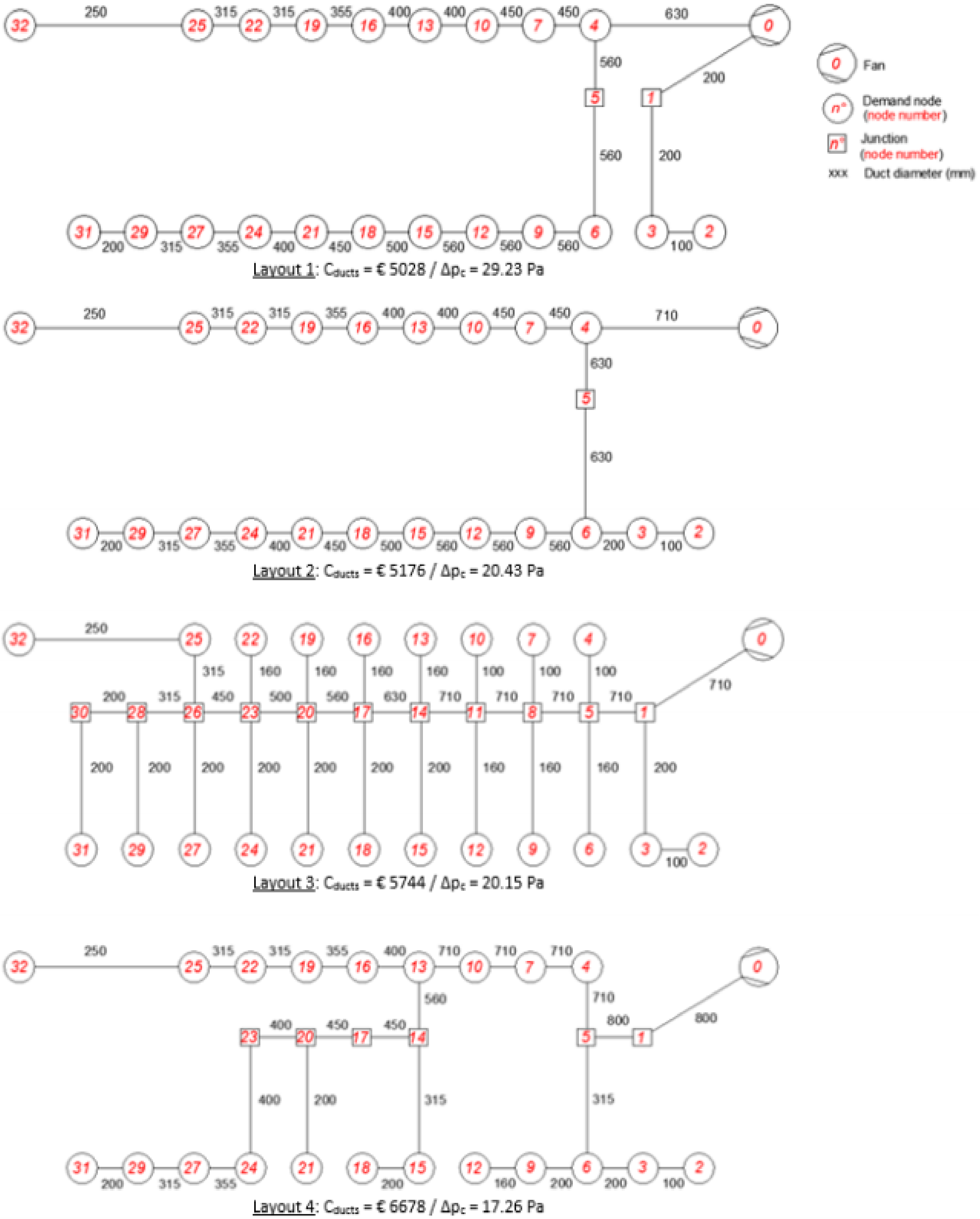

Fig. 3: four example solutions generated with the ADND optimization algorithm. Each layout has a different ductwork cost Cducts (in euro), and pressure drop over the critical path Δpc (in Pa).