Universiteit Antwerpen

This item is the archived peer-reviewed author-version of:

Design optimization of air distribution systems in non-residential buildings

Reference:
Jorens Sandy, Verhaert Ivan, Sörensen Kenneth.- Design optimization of air distribution systems in non-residential buildings
Energy and buildings - ISSN 0378-7788 - 175(2018), p. 48-56
Full text (Publisher's DOI): https://doi.org/10.1016/J.ENBUILD.2018.07.018
To cite this reference: https://hdl.handle.net/10067/1522940151162165141

uantwerpen.be
Institutional repository IRUA

Design Optimization of Air Distribution Systems in Non-Residential Buildings

Sandy Jorens[a,*], Ivan Verhaert[a], Kenneth Sörensen[b]

[a] *Energy and Materials in Infrastructure and Buildings (EMIB - HVAC), University of Antwerp, Campus Groenenborger (Building Z), Groenenborgerlaan 171, 2020 Antwerp, Belgium*

[b] *University of Antwerp Operations Research Group (ANT/OR), City Campus, Prinsstraat 13, 2000 Antwerp, Belgium*

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.

Keywords: air distribution system design, ductwork layout, duct and fan

*Corresponding author: sandy.jorens@uantwerpen.be

Declarations of interest: none

sizing, heuristic optimization algorithm, multi-start local search, test case

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 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, 9, 10, 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. 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, since such a network consists only of one or more trees (i.e., graphs that do not contain loops). The output of the algorithm is either a tree of minimum total cost that connects all demand nodes to the fan and fulfills all constraints, or multiple subtrees where each subtree has its own fan. As an example, four different outcomes of the algorithm, applied on the floor plan in figure 1, are represented in figure 5.

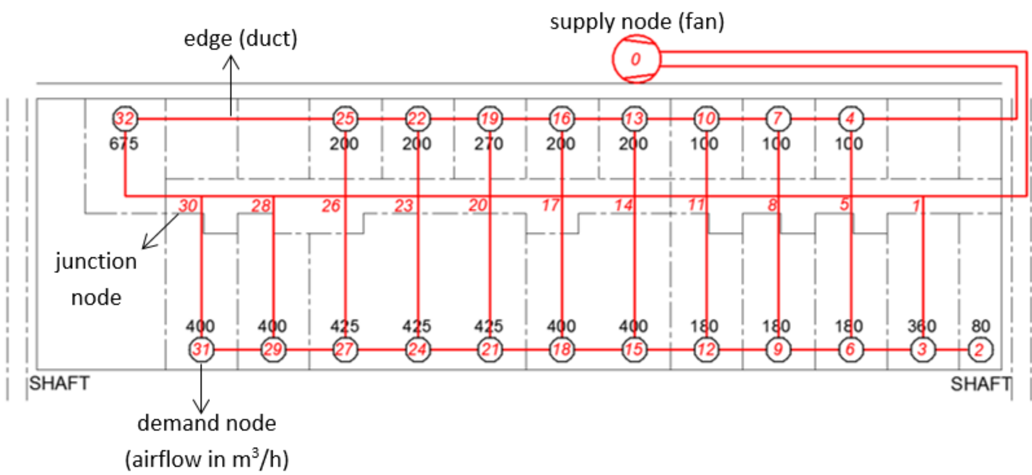

Figure 1: representation of one floor in an office building as a graph G with 51 edges and 33 nodes, from which 1 supply node (i.e., a fan), 11 junction nodes, and 21 demand nodes

The objective function is defined as the sum of the duct and fan costs:

$$\text{minimize} \;\; \text{cost} = \sum_{d \in D} \sum_{t \in T} x_{td} \, C_{td} \, L_d \; + \; \sum_{f \in F} \sum_{s \in S} x_{sf} \, C_{sf} \tag{1}$$

In the mathematical formulation of the cost x_{td} is a binary decision variable that determines if duct d is selected to be of type t ($x_{td} = 1$) or not ($x_{td} = 0$). Likewise for the fan selection, i.e., x_{sf} equals 1 when a fan of size s is selected at location f, and equals 0 when a fan of size s is not selected. The first term of formula 1 represents the ductwork cost, which depends on the total length L_d of each duct d, as well as the type t selected for duct d, and the cost per unit of length for a duct of type t. Each duct type is characterized by a different nominal duct size (selected from a list of commercially available types T) and material (e.g., aluminum, galvanized steel or flexible ducts), resulting in a certain unit cost per meter C_{td} for circular ducts. The second term of equation 1 represents the material cost of the fan(s), where

C_{sf} is the cost of a fan of type s. Each fan type is determined, for example, by its performance curves, size, and its application field (centrifugal or axial fan).

2.2. Constraints

The objective function is limited by numerous physical and external constraints, which define the viability of the air distribution system design. The first class of constraints (e.g., the mass balancing constraints) are determined by the physical laws that act upon the air distribution network and are crucial for the correct functioning of the air distribution system. The second class of constraints, i.e., external constraints, are imposed by the fact that the air distribution system needs to be built in an environment that does not allow infinite degrees of freedom. For example, the maximum allowable duct diameter usually depends on the height of the false ceiling in the building. For now, we only list the constraints that are integrated in the heuristic optimization algorithm, addressed in section 3:

mass balance - According to the mass balance or mass conservation law, the mass of air (expressed in kg) flowing into a node in the air distribution network per unit of time (in s) is equal to the mass of air flowing out of this node and must be fulfilled for each node $n \in N$:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{2}$$

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. The maximum allowable pressure is predetermined and depends amongst others by the size of the installation and local legislation.

$$p_c \leq p_{max} \tag{3}$$

where:

- p_c = total pressure loss of the critical path (Pa);
- p_{max} = maximum allowed pressure (Pa)

pressure balance - The pressure balancing constraint states that the total pressure loss of each path in the air distribution network is the same:

$$\sum_{i \in I} \Delta p_i = p_{fan} \tag{4}$$

where:

- Δp_i = total pressure loss in duct section i, where $i = 1, 2, \ldots, I$ (Pa),
- I = the set of duct sections in duct path l,where $l \in L$ (-),
- L = total set of duct paths in the air distribution network (-),
- p_{fan} = total fan pressure (Pa)

If the pressure balancing constraint is not satisfied, balancing dampers are required to balance the air flow in the air distribution system. Since every balancing damper results in an extra pressure loss, and thus an extra cost, the optimization method should aim to meet this constraint as good as possible.

air velocity - Limitations are set on the air velocity to reduce duct noise:

$$v_{i,min} \leq v_i \leq v_{i,max} \tag{5}$$

where:

- v_i = velocity in duct section i, where $i = 1, 2, \ldots, n$ (m/s),
- n = the number of duct sections in the air distribution system (-),
- $v_{i,min}$,$v_{i,max}$ = minimum and maximum allowable velocity in duct section i (m/s).

nominal duct sizes - The set of commercially available duct sizes, to choose a duct from, is limited. Each duct can only be of one type.

space limitations - The maximum allowable duct diameter depends on the available building space:

$$D_i \leq D_{i,max} \tag{6}$$

where:

- D_i = diameter in duct section i, where $i = 1, 2, \ldots, n$ (m),
- n = the number of duct sections in the air distribution system (-),
- $D_{i,max}$ = maximum allowable diameter in duct section i (m).

telescopic constraint - The diameter of the upstream duct D_{up} (m) must be greater than, or equal to the diameter of the downstream duct D_{down}(m):

$$D_{up} \geq D_{down} \tag{7}$$

With exception of the pressure balancing constraint, all the restrictions are mandatory, unless otherwise required by the designer. The ADND optimization method aims to meet the pressure balancing constraint as much as possible, but a solution that does not comply 100% with this limitation will not be excluded.The formula for the calculation of the duct pressures can be found in section 3.3. The formulation of the ADND optimization problem clearly shows that it is a mixed-integer, non-linear optimization problem. The discrete decision variables (e.g., the type of each duct), also make it a combinatorial optimization problem. Since exact methods are subject 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 and can be best approached by metaheuristic techniques.

3. Heuristic optimization algorithm

To solve the ADND optimization problem, we have opted for a multi-start local search strategy that has 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 a network configuration meets the maximum pressure and space limitations constraints, and thus is considered as 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 ADND optimization algorithm is represented as a flowchart in figure 2, and all steps are discussed in detail in the next subsections for large air distribution systems with one centralized fan. The programming language Python has been selected to implement the algorithm.

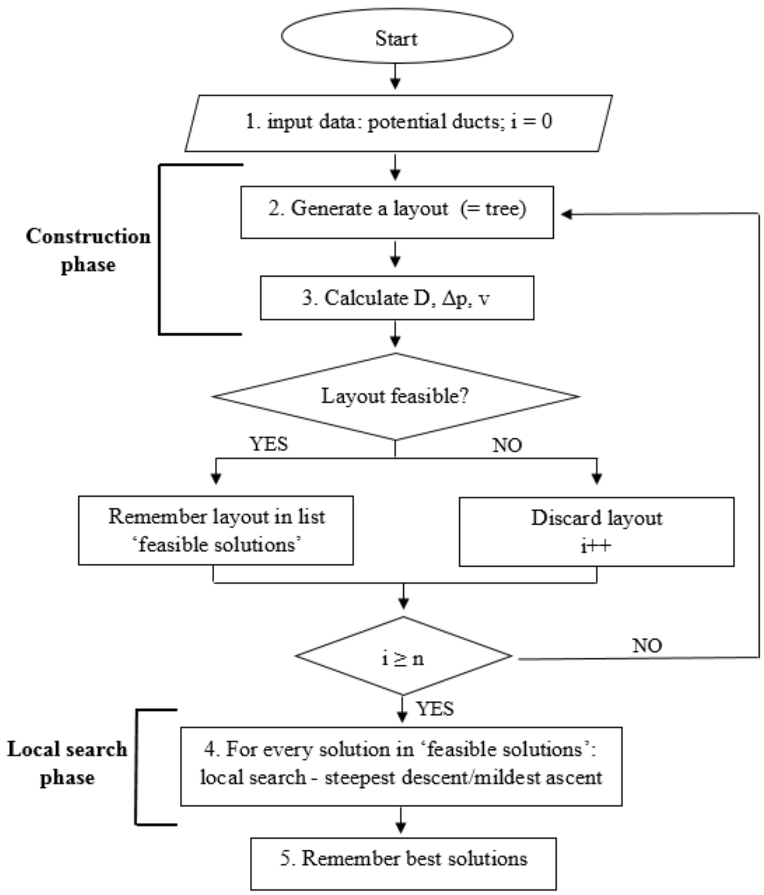

Figure 2: flowchart of the ADND optimization algorithm

3.1. 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 4). The input can be seen as an undirected weighted graph with the fan as root node (i.e., node 0) 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.

3.2. 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 is 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. As an example, potential layouts are represented in figure 5. 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 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 4). 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 unnecessary ducts in the air distribution network are removed, i.e., ducts through which no air flows. In order to know which ducts are inessential, 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. This is necessary to calculate the pressure drop over each path, and thus the required fan pressure. 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.

3.3. Calculation of the ducts' dimensions, velocities, and pressure drops

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.

The ducts' air flow rates are calculated using formula 2. Next, all diameters are determined using the average velocities that are associated with them and given as input data (see section 3.1). The obtained diameters still have to be converted to nominal duct diameters that are commercially available. Each calculated diameter is bounded by two nominal duct diameters, and it's the upper limit that is selected to replace the initial calculated diameter. These adjustments, of course, result in new air velocities. Next, the pressure drop over each duct is determined. The pressure drop due to friction for a constant-area duct is given by the Darcy-Weisbach equation:

$$\Delta p_i = f \frac{L_i}{D_{H,i}} \frac{\rho v_i^2}{2} \tag{8}$$

where:

- Δp_i = pressure drop over duct section i (Pa),
- L_i = length of duct section i (m),
- $D_{H,i}$ = hydraulic diameter of duct section i (m),
- v_i = air velocity in duct section i (m/s),
- f = friction factor (-),
- ρ = air density (kg/m^3).

In this paper, the air density and friction factor are assumed to be constant in the whole air distribution system.

The pressure drop over each path in the generated layout equals the sum of the pressure drops over all the ducts that are part of the path.The path with the highest pressure loss is defined as the critical path, and is higly correlated to the fan power.

3.4. Local search phase: steepest descent – mildest ascent method

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 material costs. 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.

3.4.1. Duct reduction

During the first step of the local search phase, the total cost of the ducts is minimized by reducing the ducts one by one, starting with the largest ducts. 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. Ducts will be reduced until all paths have a pressure drop larger than, or equal to the maximum allowable pressure.

First three lists are generated. The first one, L_1, lists all ducts that are part of a path with a pressure loss greater or equal than the maximum allowable pressure p_{max}. The second list, L_2, contains all ducts that cannot be reduced anymore due to the velocity constraint (see formula 5). Initially this list is empty. The last list, L_3, contains ducts that are eligible to be reduced. These are the ducts that are part of the path with minimum pressure loss, and are not listed in the first two lists. The first duct that is selected to be decreased with one size is the largest duct in L_3. When two or more ducts have the largest diameter, the duct that is located most downstream will be decreased first. This is to ensure that the telescopic constraint is met. Subsequently, the velocity in this duct will be recalculated. If the velocity constraint is not fulfilled, the original diameter of the duct is selected again, and this duct together with all upstream ducts with the same diameter, are added to the second list. On the other hand, if the velocity constraint is fulfilled, the new diameter is retained, and the pressure drop over all paths are recalculated. L_1 and L_3 are adjusted and a new duct from L_3 is selected to be decreased. These steps are repeated until the pressure loss of every path is greater than, or equal to the maximum allowable pressure. In this case L_3 will be empty. However, in case that there are no candidate ducts listed anymore in L_3, but the minimum pressure path still has a lower pressure drop than p_{max}, the path with the second lowest pressure drop will be selected to draw up L_3 ,and so on. This until all ducts of the solution are included in L_1 and L_2.

3.4.2. Telescopic constraint

Following the duct reduction phase, each duct in every path has to be checked to see if it satisfies the telescopic constraint. Nothwithstanding the fact that this constraint was taken into account in the previous step, some ducts may still not meet this constraint. If the telescopic constraint is not satisfied, the duct(s) located downstream to the smaller duct, will be decreased so that they have equal or smaller diameters. Figure 3 gives a simplified example of a situation where the telescopic constraint is not fulfilled after the duct reduction phase. Figure 3A represents the initial ductwork configuration. Both paths have a pressure drop that is lower than the maximum permitted pressure drop, and thus the duct reduction phase can be carried out. Since path B is the path with minimum pressure, the largest duct from this path is selected first to be decreased. Both duct 1 and 2 are eligible to be decreased, starting with the duct located most downstream, i.e., duct 2. The pressure drops over path A and B are recalculated. If both pressure drops exceed the maximum permitted pressure (figure 3B), the ductwork configuration has to be checked to see if it fulfills the telescopic constraint. As can be seen in figure 3B, this constraint is satisfied by path B, but not by path A. Duct 3 has to be decreased as well, so that its diameter is smaller than, or equal to the diameter of duct 2 (figure 3C).

3.4.3. Duct increase

In the last step of the local search phase, the ducts in the network are increased one per one, until the maximum pressure constraint is satisfied. Contrary to section 3.4.1, the mildest ascent approach is now being followed. This means that the smallest ducts are selected first to be increased, since they worsen the objective function, i.e., minimization of the costs, the least.

First one path is selected that exceeds the maximum allowable pressure p_{max}, and all ducts in this path are eligible to be increased. The ducts will be increased one per one, starting with the smallest diameter, until the pressure drop of the path is smaller than, or equal to p_{max}. If two are more ducts have the smallest diameter, the duct located most upstream will be increased first. These steps are repeated until all paths meet the maximum pressure constraint, and thus a local optimum is reached.

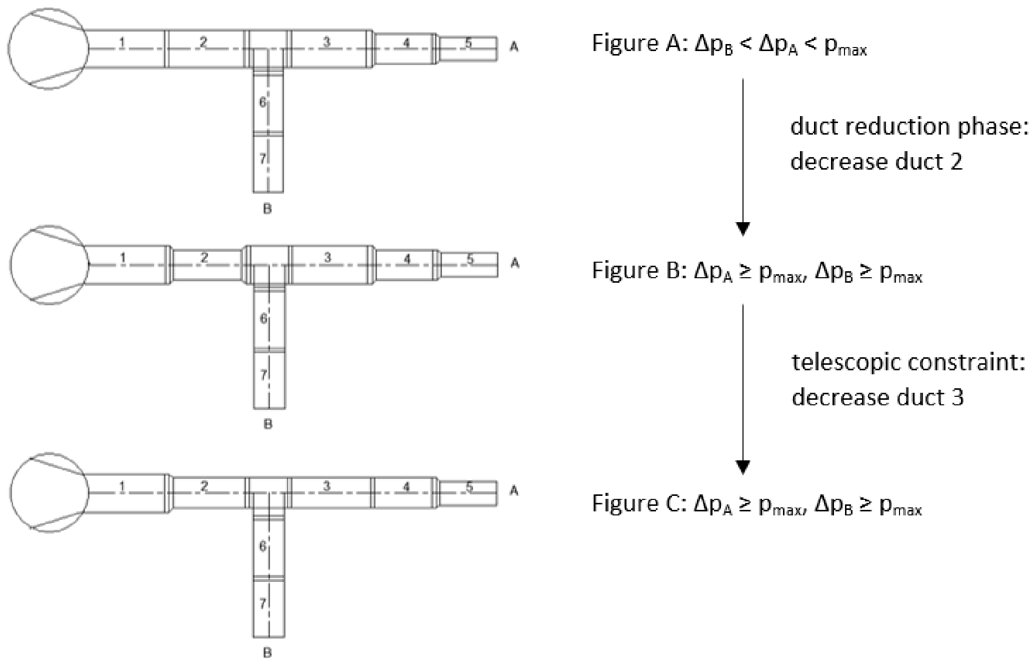

Figure 3: simplified example where the telescopic constraint is not met after the duct reduction phase (figure B). In figure C, the telescopic constraint is met again

3.5. Solutions

The x 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 (see section 4.2). Since the ADND problem is formulated as a single objective optimization problem, many intermediate solutions with minor variations in the layout are generated for every solution with a significant change in layout. However, these intermediate solutions are less worth knowing for the design engineer, since they hardly affect the total cost or the pressure drop over the critical path. By generating sufficient solutions or by adjusting the maximum pressure and space limitation constraints, solutions with large variations in the layout will also be generated. It is then up to the design engineer in charge to make the trade-off between the material costs and fan pressure.

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 m^3/h. The location of all demand nodes, and the associated air flow rates (in m^3/h) are indicated in figure 4. The fan is located in the technical room on the top floor of the building.

4.1. Input data

As stated in section 3.1, 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 (i.e., the fan), potential junctions and demand nodes, and the air flow rates that are associated to the corresponding demand nodes (in m^3/h). Figure 4 gives a graphic representation of the input data. In total there are 33 nodes, from which 1 supply node (i.e., node 0), 11 junctions, and 21 demand nodes. 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 5 m/s. The maximum permitted pressure drop is set at 60 Pa, and the maximum diameter at 800 mm. For now, only circular ducts are considered. In practice, ducts of this size are rarely installed, as rectangular ducts are much more frequently used. Rectangular ducts score less in terms of energy and acoustic comfort, but take up less space. The inclusion of rectangular ducts in the ADND optimization algorithm is for future research.

For this test case, the number of layout generations n (see figure 2) is set to 250, and the air density and friction factor are set equal to 1.225 kg/m^3 and 0.015 respectively. The friction factor is an average and rounded value calculated from different test cases in EES (Engineering Equation Solver) using the simulation model described by Jorens et al. [20].

4.2. Results

Table 1 displays the five best overall solutions generated with the ADND optimization algorithm, wherin the very best solution in terms of material costs (i.e., solution 1), is also shown graphically in figure 5 (i.e., layout A). For each solution in table 1 the air volume flow rate (in m^3/h), ductwork costs (in euro), pressure loss of the critical path (in Pa), and the pressure

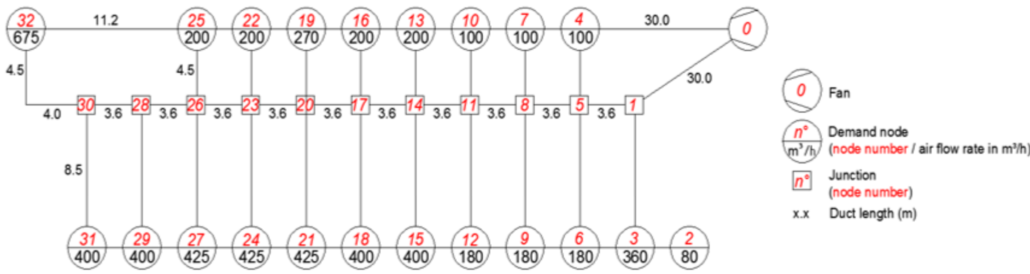

Figure 4: graphic representation of the input data of one floor in an office building

difference between the path with the maximum pressure and the path with the minimum pressure (in Pa) is given. According to the pressure balancing constraint (formula 4) , the latter parameter should be as low as possible. The total ductwork costs are calculated using the price catalog of Lindab.

Table 1: 5 best solutions generated with the ADND optimization algorithm. Following values are displayed for each solution from left to right: volume flow rate (in m^3/h), cost of ducts (in euro), pressure loss of the critical path (in Pa), and pressure difference between the critical path and the path of minimum pressure loss (in Pa)

	$\dot{V}$ (m^3/s)	C_{ducts} (euro)	Δp_c (Pa)	$\Delta p_c - \Delta p_{min}$ (Pa)
1	5900	5027.76	29.23	6.88
2	5900	5028.75	29.23	7.65
3	5900	5044.95	29.23	10.48
4	5900	5054.49	29.23	7.65
5	5900	5059.63	35.91	21.02

Since the objective function is limited to the minimization of the ductwork costs, these solutions all have a similar layout. It is only from the fifth solution that there is a visible change in the layout. Therefore it is important to not only compare the best solutions, but also to include the more expensive solutions generated with the ADND optimization algorithm.

As an example, three more expensive solutions, but with a completely different layout are also graphically represented in figure 5. 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). These three layouts were generated by adjusting the maximum pressure and space limitations (i.e., 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 fan pressure. Layout A, for example, is with a total ductwork cost of 5028 euro the cheapest solution. However, it can be more beneficial to select a slightly more expensive layout, e.g. layout B with a total ductwork cost of 5176 euro, which has a lower pressure drop over its critical path (i.e., 20.43 Pa compared to 29.23 Pa). From an energetic point of view, layout D scores the best out of the 4 selected layouts with a pressure loss over its critical path of only 17.26 Pa, but this solution may not outweigh the additional material costs, i.e., an extra 32.8 % compared to layout A. Especially when we consider the entire office building instead of only one floor. The additional costs will increase tremendously in this case.

5. Conclusion and future research

5.1. Conclusion

The results displayed in figure 5 clearly show that the layout has a great influence on the air distribution system's cost and fan pressure. 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 focus 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 varying 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 costs and fan pressure.

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 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. However, 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.

5.2. Future research

Interesting topics for future research are:

- The transformation of the ADND optimization problem as a single objective problem to a multi-objective optimization problem. Objectives, such as the minimization of the installation costs, and energy use, the maximization of the users' comfort, or the minimization of the life cycle costs, can be integrated in the problem formulation,
- The integration of both circular and rectangular ducts in the optimization algorithm,
- The implementation of fittings (i.e., junctions, elbows, . . .) ,
- The implementation of other heuristic optimization techniques,
- The integration of variable air volume systems in the algorithm,
- The application of te algorithm on air distribution systems with multiple fans,
- The application of the algorithm on multiple real-life test cases with varying characteristics.

6. References

[1] D. D'Agostino, B. Cuniberti, and P. Bertoldi. Energy consumption and efficiency technology measures in european non-residential buildings. *Energy and Buildings*, 153:72–86, 2017.

[2] L. Pérez-Lombard, J. Ortiz, and C. Pout. A review on buildings energy consumption information. *Energy and Buildings*, 40:394–398, 2008.

[3] Y. Asiedu, R. W. Besant, and P. Gu. HVAC duct system design using genetic algorithms. *HVACR Research*, 6:149–173, 2000.

[4] J. H. Buys and E. H. Mathews. Investigation into capital costs of HVAC systems. *Building and Environment*, 40:1153–1163, 2005.

[5] R. Gao, K. Liu, A. Li, Z. Fang, Z. Yang, and B Cong. Study of the shape optimization of a tee guide vane in a ventilation and air-conditioning duct. *Building and Environment*, 132:345–356, 2018.

[6] M. Mossoly, K. Ghali, and N. Ghaddar. Optimal control strategy for a multi-zone air conditioning system using genetic algorithm. *Energy*, 34:58–66, 2009.

[7] M. C. E. Manuel, P. T. Lin, and M. Chang. Optimal duct layout for hvac using topology optimization. *Science and Technology for the Built Environment*, 24:212–219, 2018.

[8] ASHRAE. *ASHRAE Handbook - Fundamentals*, chapter 21: Duct design, pages 21.1–21.67. American Society of Heating, Refrigeration and Air-Conditioning Engineers, 2009.

[9] K. F. Fong, V. I. Hanby, and T. T. Chow. A robust evolutionary algorithm for HVAC engineering optimization. *HVACR Research*, 14:683–705, 2008.

[10] T. Kim, J. D. Spitler, and R. D. Delahoussaye. Optimum duct design for variable air volume systems - part 1: problem domain analysis of vav duct systems and part 2: optimization of vav duct systems. *ASHRAE Transactions*, 108:96–127, 2002.

[11] R. J. Tsal and M. S. Adler. Evaluation of numerical methods for ductwork and pipeline optimization. *ASHRAE Transactions*, 93, 1987.

[12] S. Jorens, K. Sörensen, I. Verhaert, and A. De Corte. Air distribution system design optimization in non-residential buildings: Problem formulation and generation of test networks. *Journal of Building Engineering*, 12:60–67, 2017.

[13] J. S. Moon, T. G. Lee, J. H. Moon, J. H. Lee, and H. Yoo. A modified T-method simulation for multi-fan duct systems. *Indoor and Built Environment*, 15:137–145, 2006.

[14] Y. Asiedu. *Life-cycle cost analysis and probabilistic cost estimating in engineering design using an air duct design case study*. PhD thesis, University of Saskatchewan, 2000.

[15] K. Sörensen and F. W. Glover. Metaheuristics. In S. Gass and M. Fu, editors, *Encyclopedia of operations research and management science*, pages 960–970, New York, 2013. Springer.

[16] A. De Corte and K. Sörensen. An iterated local search algorithm for water distribution network design optimization. *Networks*, 67:187–198, 2016.

[17] W. G. Zong. Particle-swarm harmony search for water network design. *Engineering Optimization*, 41:297–311, 2009.

[18] J. Janssens, L. Talarico, and K. Sörensen. A hybridised variable neighbourhood tabu search heuristic to increase security in a utility network. *Reliability Engineering System Safety*, 145:221–230, 2016.

[19] A. Ghahramani, S. A. Karvigh, and B. Becerik-Gerber. Hvac system energy optimization using an adaptive hybrid metaheuristic. *Energy and Buildings*, 152:149–161, 2017.

[20] S. Jorens, I. Verhaert, and K. Sörensen. Design optimization of air distribution systems in non-residential buildings. *Clima 2016: proceedings of the 12th REHVA World Congres*, 9:1–10, 2016.

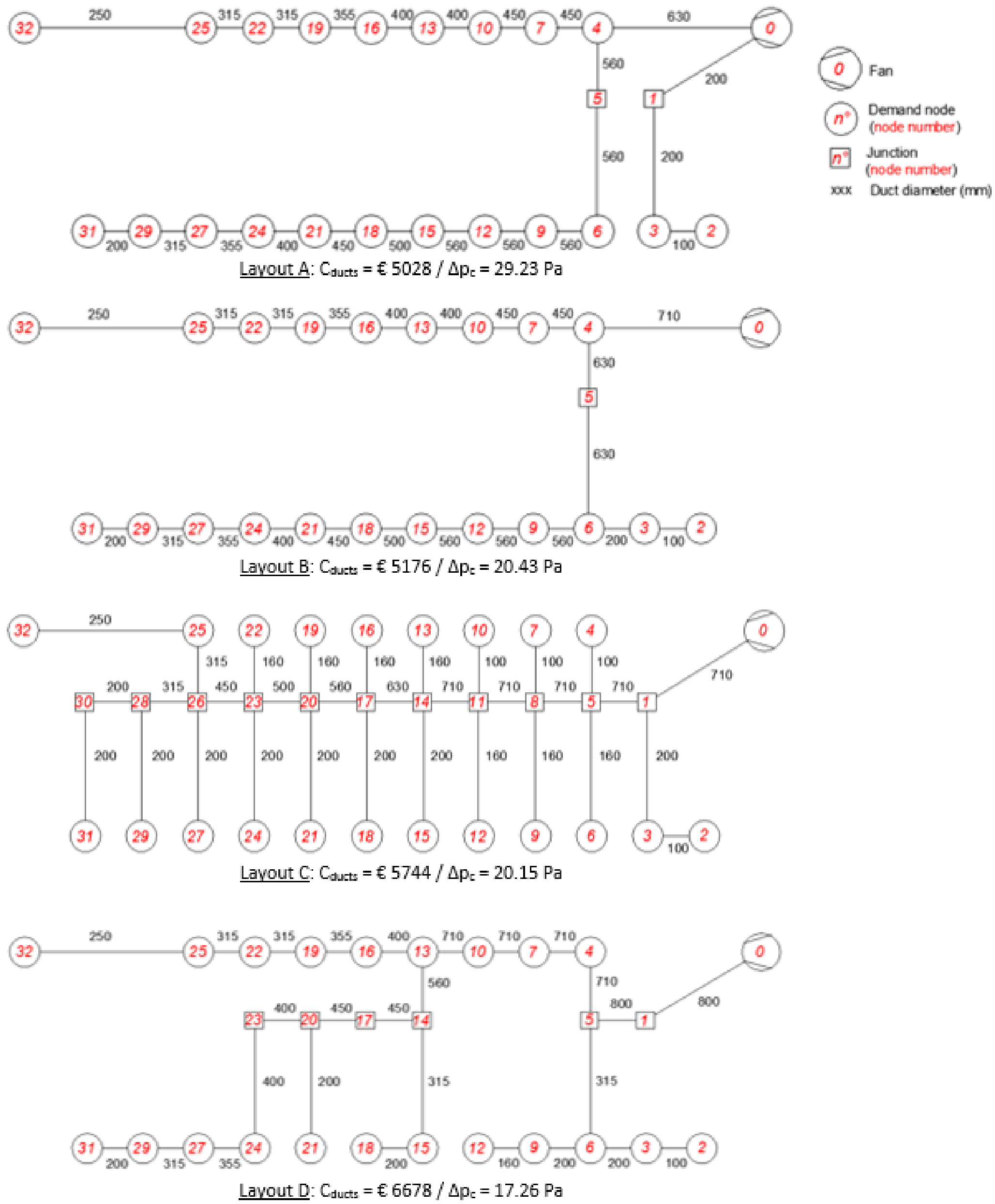

Figure 5: four example solutions generated with the ADND optimization algorithm. Each layout has a different ductwork cost C_{ducts} (in euro) ,and pressure drop over the critical path Δp_c (in Pa)