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Air Distribution System Design Optimization in Non-Residential Buildings: Problem Formulation and Generation of Test Networks

Sandy Jorens\textsuperscript{a,}\textsuperscript{*}, Kenneth Sörensen\textsuperscript{b}, Ivan Verhaert\textsuperscript{a}, Annelies De Corte\textsuperscript{b}

\textsuperscript{a}Energy and Materials in Infrastructure and Buildings (EMIB - HVAC), University of Antwerp, Campus Groenenborger (Building Z), Groenenborgerlaan 171, 2020 Antwerp, Belgium

\textsuperscript{b}University of Antwerp Operations Research Group (ANT/OR), City Campus, Prinsstraat 13, 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 locations of the fans, is an important determinant of the installation’s cost and performance. Nevertheless, the layout is not explicitly taken into account in existing duct design methods. 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. This paper aims to outline the current state-of-the-art in air distribution system design and highlights the main shortcomings. Additionally, previous research is extended by presenting a novel problem formulation that integrates the layout decisions into the optimization problem. In this problem, called the air distribution network design optimization problem, the optimal air distribution system configuration, i.e., 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. This paper also motivates the need for benchmark instances to evaluate the performance of existing or new developed optimization methods and advance future research in the field of air distribution system design optimization. A test network generator is developed in this research to generate such a set of instances.

\textsuperscript{*}Corresponding author: sandy.jorens@uantwerpen.be

1. Introduction

One of the most energy-consuming and cost expensive (up to 35% in Belgium) parts of a heating, ventilation and air conditioning (HVAC) system is the air distribution system [1, 2, 3]. 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 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.

A large number of papers have been dedicated to the design of air distribution systems or networks and several optimization methods have been developed. However, most methods only focus on the second phase, i.e., they only determine the size of each duct and/or fan in the system and consider the layout to be given [4, 5, 6]. The very few methods that do take the layout into consideration, are limited to the automatic generation of the
air distribution network without optimizing it. The generation of the layout and the dimensioning of the system are treated as independent decisions [7]. Clearly, the layout of the air distribution system and the duct and fan sizes are interrelated decisions that jointly influence the quality of the system [8, 9, 10].

In this paper, we therefore formulate a novel optimization problem, which we call the air distribution network design (ADND) problem, in which both the layout decisions and the duct and fan type decisions are taken simultaneously. The development of an optimization algorithm, however, is outside the scope of this paper. A second problem with the current state of the art is that, due to lack of realistic benchmark instances [11, 12], current optimization methods have not been adequately tested, and thus no strong conclusions can be drawn on their performance in realistic circumstances, nor can their performance be objectively compared to other existing methods. Moreover, if we want to develop a new optimization method in the future that integrates both the layout and the duct and fan sizing, benchmark instances are required to evaluate the performance of this new optimization method. Therefore, we develop a test network generator in this paper that is able to generate realistic artificial benchmark instances with varying characteristics.

In the next section this paper provides a thorough review of previously developed methods for duct size optimization and highlights their main shortcomings. Section 3 gives insight into the novel air distribution network design problem and section 4 covers the test network generator. Conclusions and pointers for future research are addressed in the last section.

2. Literature Review: Air Distribution Network Design (ADND)

Since the 1960s, a lot of research has been dedicated to the simulation and optimization of air distribution systems [13, 14, 6, 15, 16]. Numerous design methods have been developed to support the design engineer in the second phase of the design process, namely the duct sizing and fan selection, starting from a given ductwork layout. Generally, current duct design methods can be subdivided in two main categories.

The first category consists of non-optimizing methods that rely on simple heuristics which do not explicitly take into account prevailing local economic conditions. Instead of optimizing an objective function, these methods only use assumptions for variables such as the air flow velocity and friction losses, which are based on rules of thumbs and the designer’s experience [17, 18].
The obtained designs are workable, but not necessarily optimal. The Equal Friction and Static Regain method are the two most commonly used methods in this category \cite{4, 19, 18}. In the first method, the frictional pressure drop per unit length of the duct (Pa/m), i.e., the friction rate, is maintained constant throughout the duct system, where the frictional pressure drop is associated with the duct wall friction. This method is straightforward but involves judgement in the selection of the friction rate, since there is a wide range of possible values for the friction rate. The objective of the static regain method is to obtain the same static pressure at diverging flow junctions and before each terminal unit by changing downstream duct sizes (Figure 1). This method of duct sizing is based on Bernoulli’s equation, which states that a reduction of velocities results in a conversion of dynamic pressure into static pressure. The velocity for the root section is an arbitrary parameter and depends on the design engineer’s experiences.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure1.png}
\caption{Schematic representation of pressure distribution for static regain design, where $p_t$ = total pressure, $p =$ static pressure and $p_v =$ velocity or dynamic pressure \cite{18}}
\end{figure}

The second category consists of optimization methods. Their main goal is to determine duct sizes according to optimal pressure losses and select a fan according to the optimal fan pressure that minimizes life cycle costs (LCC) \cite{1, 20, 15, 21}. The Reduced Gradient \cite{22}, Quadratic Search and the Modified Lagrange Multiplier methods \cite{23} are some of the many computer-aided
numerical optimization methods used for network optimization. These methods are all continuous methods and thus, they are not adequate to deal with discrete parameters such as nominal duct sizes. In 1968 Tsal and Chechik developed a method based on Bellman’s dynamic programming method (1957) [6]. Unfortunately, when exact methods such as dynamic programming are used for large combinatorial optimization problems like the ADND optimization problem, computing time increases exponentially with the size of the problem (a phenomenon which is known as combinatorial explosion). This results in excessively long computation times [16].

The most widely known optimization method is the T-method [15], which is also based on dynamic programming [24]. The method’s objective is to find duct sizes and select a fan so that the system’s life-cycle cost is minimized. The calculation procedure of the T-method consists of three main steps. First the entire duct system is condensed into a single duct section for finding the ratios of optimal pressure losses using sectional aerolic characteristics (= system condensing). After calculating the optimal system pressure loss in the second step, a fan is selected. Last, the system pressure is distributed throughout the system sections (a step which is called system expansion). Although this method is recommended by ASHRAE (American Society of Heating, Refrigeration and Air Conditioning Engineers) [4], it is hardly used in practice. Asiedu [17, 1], Mathews et al. [25], Moon et al. [12] and Shiu et al. [26] list the main shortcomings of the T-method for large complex ADNs. Moon et al., for example, state that the computation procedure of the T-method is too complicated in actual duct design, when the designer is faced with many constraints and requirements (e.g., limitations on space, noise level, pressure losses and duct sizes). Asiedu, on the other hand, states that metaheuristic techniques such as evolutionary metaheuristics are needed to tackle large complex network designs and proposes a Segregated Genetic Algorithm. Contrary to exact optimization algorithms, metaheuristics do not guarantee the absolute optimum of the obtained solutions, but aim to find a high-quality solution in an acceptable computing time. Other (meta)heuristics that were used to deal partly or completely with the duct optimization problems are for example Simulated Annealing [16], the Nelder-Mead or downhill simplex method [6] and a robust evolutionary algorithm [5]. Although recent papers have been published [14, 27, 28, 29], these mainly re-iterate the same ideas of previous research [17, 19, 15], i.e., they focus only on the duct sizing and fan selection and, more important, the objective function of the ADND optimization problem is largely the same as the objective
functions defined in previous research.

In general, two main shortcomings can be identified that characterize previous research on ADND optimization. First, all developed optimization methods are limited to the second phase of the design process, namely duct sizing and/or fan selection, starting from a given network layout. 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. Moreover, during the design phase external changes in the building often occur (e.g., modified air flow rates in one or more rooms and adapted dimensions of the false ceiling), which have a significant influence on the network configuration. For example, if the required air flow rate has been increased in one or more rooms at the end of the air distribution system layout, the dimensions of all the ducts located upstream to the respective rooms, may have to be increased as well. Consequently, some of the ducts may not fit anymore under the false ceiling, resulting in a recalculation of the complete layout. Existing methods are not able to quickly respond to such design changes, causing a loss of valuable time and money. Second, previously developed methods are often tested solely on the ASHRAE benchmark network (figure 2). This network, however, does not reflect a realistic ADN in non-residential buildings. On the supply side, the ASHRAE network contains only one fan (resource node) which provides six terminal units (demand nodes) of air. Realistic networks in hospitals or large office buildings can have hundreds of terminal units and multiple fans. Due to lack of benchmark instances, current optimization methods have not been adequately tested. Testing on a single network leads to overfitting of the method, and thus no general conclusions can be drawn on their performance. As a result, air distribution systems are generally largely designed manually, and rely for their performance on the knowledge and experience of the engineer in charge of the design. Clearly, the field of air distribution design would benefit greatly from models and methods that allow more advanced automation and optimization.

Abovementioned shortcomings can be tackled through the development of optimization methods that are able to calculate the optimal air distribution system configuration, i.e., both the layout and duct and fan sizes. In this paper, we lay the necessary groundwork for this development by formulating the problem, which we call the ADND optimization problem, as a non-linear combinatorial optimization problem. In order to validate the performance of such a method and to evaluate its robustness, benchmark instances are
required. A test network generator is developed in section 4 that can generate such realistic artificial benchmark instances. The next section introduces the novel ADND optimization problem.

3. The Air Distribution Network Design Optimization Problem

In this section, we pave the way for the development of a new ADND optimization method by formulating the problem, which we call the ADND optimization problem as a non-linear combinatorial optimization problem. As mentioned, the optimization of both the layout and the duct and fan sizes are interrelated decisions that should be taken simultaneously. In contrast with existing methods, we tackle this issue by integrating the layout of the ADN into the problem formulation. In this paper we introduce the resulting novel optimization problem. The development of an optimization algorithm to solve this problem is left for future research.
In this research an air distribution system 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 and given as input in text file format to the optimization algorithm. This input can be obtained from building plans or from the benchmark instances generated in section 4. The output of the optimization algorithm will be a spanning tree (i.e., a tree that connects each node with the fan) of minimum total cost that satisfies all constraints. It can be either one spanning tree with one large fan or multiple subtrees where each subtree has its own fan (figure 3).

Figure 3: schematic representation of the input (left illustration) and possible outputs (right illustrations) of the optimization algorithm

Although real-life air distribution systems should be evaluated on multiple criteria (e.g., installation cost, life-cycle cost, energy consumption and
noise levels), minimization of the installation cost is generally seen as the most important objective in practice. We therefore define the ADND optimization problem as a single-objective optimization problem. In a later stage of the research, the problem will be defined as a multi-objective optimization problem. For now, the objective function is defined as the sum of the duct costs and the fan costs:

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

(1)

In the equation $x_{td}$ is a discrete 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 $T$) and specific material characteristics, 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).

Significant for the design of air distribution systems is the large number of constraints which need to be satisfied. Generally these can be divided in two main categories: physical and external constraints. The physical constraints such as mass and pressure balancing and the velocity constraint are determined by the physical laws that act upon the air distribution system and are decisive for the proper functioning of the system. The 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. The mass balance or mass conservation law states that the mass of air (expressed in kg) flowing into a node in the network per unit of time (in s) equals the mass of air flowing out of this node and must be satisfied for each node $n \in N$:

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

(2)

The total airflow rate in the entire air distribution system, i.e., the airflow
that is delivered every second by the fans in the system, equals the sum of the desired airflow rates at each terminal unit. These airflow rates are assumed to be given. Note that the terminal flow rate requirements vary from room to room.

The pressure balancing constraint requires that the total path pressure losses are the same for all duct paths in the network:

$$\sum_{i \in I} \Delta P_i = P_{fan}$$ (3)

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

If this constraint is not fulfilled, balancing dampers must be installed to balance the air flow in the system. Since every balancing damper induces extra pressure losses and thus an extra cost, the designer should aim to meet this constraint. The pressure drop (expressed in Pa) due to friction for a constant-area duct is given by the Darcy-Weisbach equation:

$$\Delta p = f \frac{L}{D_H} \frac{\rho v^2}{2}$$ (4)

where $f =$ the friction factor (dimensionless), $L =$ the duct length (m), $D_H =$ the hydraulic diameter (m), $\rho =$ the density (kg/m$^3$) and $v =$ the average velocity (m/s). The last grouping of terms is also called the velocity or dynamic pressure. Parameter $D_H$ is determined by the type of duct and is assumed to be given for each available type. The density $\rho$ of the medium is given and considered to be constant for the whole air distribution system. Parameter $v$ depends on the duct type that is selected and the pressure loss in that duct. Lastly, the friction factor $f$ depends on both the selected duct type and the velocity $v$.

The total pressure losses due to duct fittings (e.g., bends) are calculated by means of:

$$\Delta p = K \frac{\rho v^2}{2}$$ (5)
where $K$ is a loss coefficient that depends on the type of fitting. The $K$-values are dimensionless and are retrieved from tables [4].

The velocity constraint implies that the air velocity should be limited to reduce duct noise:

$$V_{i,min} \leq V_i \leq V_{i,max} \quad (6)$$

where:

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

The second category of constraints, i.e., external constraints can be further subdivided in mandatory (hard) and non-mandatory (soft) constraints, where the latter stands for the preferences from the designer or building owner that do not predominantly contribute to the proper functioning of the system (e.g., a preference for smaller ducts or a specific duct layout from an aesthetic point of view). Mandatory constraints, however, ensure that the obtained design is feasible (e.g., limited set of commercially available duct sizes and limited space):

$$L_i \leq D_i \leq U_i \quad (7)$$

where:

- $D_i =$ diameter of duct section $i$, where $i = 1, 2, \ldots, n$ and $D_i \in T \ (m)$,
- $L_i$ and $U_i =$ the lower and upper bounds of duct section $i$, due to velocity or geometric constraints (m).

The evaluation of the physical and external constraints requires the simultaneous solution of a set of linear and non-linear equations. These equations depend on the values chosen for the decision variables in the way mentioned before. Solving these equations can be done using software such as EES (Engineering Equation Solver), i.e., an equation based software with domain specific knowledge.

The ADND optimization problem is therefore a complex combinatorial optimization problem. It can be posited that such a problem is outside the
realm of exact methods and can be best approached by metaheuristic techniques. Sørensen and Glover define metaheuristics as “high-level, problem-independent algorithmic frameworks that provide a set of guidelines or strategies to develop heuristic optimization algorithms” [30]. Metaheuristics are also particularly well-suited in a simulation-optimization environment where either the objective function or the constraints (such as in this case) require a run from a simulation module to be evaluated. The development of such a simulation module or a metaheuristic for the ADND optimization problem, will be addressed in future research.

4. Generation of artificial air distribution systems

One of the prerequisites of developing an effective optimization method, that is able to solve the ADND optimization problem discussed in section 3, is the availability of a broad range of test cases with varying characteristics to evaluate its performance. Currently such a database of benchmark instances does not exist. To address this shortcoming, we develop a test network generator that can generate artificial benchmark instances, based on insight into real-life building plans and typical air distribution system design procedures used in practice.

By means of adjustable parameters, numerous instances of arbitrary size and characteristics can quickly be generated. For each run of the test network generator, a random “building” is generated that is characterized by the following data:

- the locations (x, y coordinates) of all the end units located in that building as well as the required air flow rate per end unit expressed in m³/h,
- all possible locations (x, y coordinate) in the building where fans can be positioned,
- all possible locations (x, y coordinate) in the building where air ducts can be installed as well as their maximum dimensions,
- the locations (x, y coordinates) and dimensions of the shafts.

Figure 4 gives a schematic representation of a small part of an instance, i.e., a single floor of an office building with multiple floors. The complete
instance would include all these data for every floor in the building. As figure 4 illustrates, these instances do not yet represent workable air distribution system configurations, as they only show where in the building ducts and fans can be optionally installed. It is up to the ADND optimization method to calculate an optimal layout with the best possible duct and fan sizes. All data are given in graphML and text file format and are intended to be used as input for future ADND optimization methods that can solve the ADND optimization problem, described in section 3.

Figure 4: Schematic representation of a benchmark instance. The air flow rates at the end units are given in m$^3$/h

To this end, multistory office buildings and universities or school buildings can be simulated. Although these types of buildings differ in their demand pattern, they generally share a similar layout. Each building can be subdivided in different zones, depending on their heating, cooling and ventilation needs, where each zone contains several rooms, which are interconnected through hallways. The supply ductwork runs typically from the centralized air handling unit or fan(s), located in a technical room or on the roof, vertically through the shafts to the several floors of the building. From there the air ducts run horizontally above the false ceiling of the corridors to the different zones and rooms that need to be ventilated and/or conditioned. The dimensions of the shafts (height and width) and the false ceiling (height) influence both the sizing and the layout of the ductwork significantly. The network generator developed in this paper and written in C++ is based on this layout principle.

Basically the generation of the benchmark instances is carried out in different phases. First, input is required from the user about the characteristics
of the building. Subsequently, the benchmark instances are generated algorithmically whereby the nodes and edges are generated sequentially in the graph. The nodes represent the junctions and end units in the air distribution network and the edges the air ducts.

The following subsections describe in detail how the benchmark instances are generated. As an example, figures 5 to 8 illustrate step by step the generation of a multistory office building with four shafts and consisting of eight zones. The figures are abstractions of buildings as we know them in real life.

4.1. User input

Requesting user input entails two major advantages. First, the user can ensure that the instances generated correspond his research needs. Second, the user input enables us to generate a wider variety of instances. This will be necessary if we want to develop and validate a new ADND optimization method that is able to tackle a wide range of realistic test cases. The following data is supplied by the user:

- The building type: office building or university,
- The number and dimensions of the shafts in the building as well as the distances between the shafts,
- The number of zones to be conditioned,
- The minimum and maximum distances between the zones,
- The size of a zone,
- The number of rooms generated for every zone, as well as the percentage of rooms to be allocated as office space, meeting room, cafeteria, aula etc.

4.2. Generation of the Nodes in the Graph

4.2.1. Generation of Shafts

Nodes of the type ‘shaft’ are characterized by a set of coordinates (x, y) and a demand that equals zero m$^3$/h. Additionally, maximum dimensions (height and width) are assigned to these types of nodes, which will determine the maximum permitted diameter of the incoming and outgoing ducts.
As can be seen in figure 5, the shafts are generated on the perimeter of a rectangle with the origin (0,0) as center. Up to eight shafts can be generated per building.

4.2.2. Generation of All Potential Supply Nodes
In a second step, the (potential) fan locations are generated, including a discrete set of potential fan types that can be installed at the corresponding locations. Each fan type is represented by its performance curves. The first supply node, i.e., the primary fan, is generated in the origin (0,0) of the graph. Additionally, for every zone in the building, secondary supply nodes are generated, where each fan and thus zone is associated with a shaft (figure 5). Besides the number of zones, the distances between the zones and the shafts can be adjusted as well by the user.

4.2.3. Generation of Zones
As mentioned in the introduction of section 4, a zone contains multiple rooms which are interconnected through hallways.

- **Hallway nodes (junctions)**
  Per fan, a rectangular grid is created, whereby only a percentage of the grid points will be allocated as hallway nodes, i.e., junctions. Both the size of the grid and the percentage are adjustable parameters.

- **Room nodes**
  All spaces in non-residential buildings can be classified into different types. Depending on the function of the building, some types of rooms may be more or less present. The ratio between the room types is given in table 1, where only the spaces with an airflow demand are taken into account. The percentages given in table 1 are assumed average values based on multiple real-life building plans. However, since these percentages can vary considerably from building to building, they are represented as adjustable parameters in the software tool.

  Every hallway node generated in the previous step, has a $\gamma\%$ chance to get assigned a room type, where $\gamma$ is an adjustable parameter. Which room type that is assigned depends on the percentages given in table 1. For instance, in the case of an office building, a small office has a 65% chance of being generated, an open office and reception each 15% and a cafeteria or restaurant 5%.
The characteristics of the various room types are given in table 2. The airflow rates and floor areas in table 2 are calculated based on the occupancy rate per room type, using the European standard EN 13779, which applies to the design and implementation of ventilation and room conditioning systems for non-residential buildings subject to human occupancy. It focuses on the definitions of the various parameters that are relevant for such systems. The air rates used in this paper are those that are associated with an acceptable air quality IDA 3 in a non-smoking area (table 3).

4.3. Generation of the Edges in the Graph

In a final phase, the software tool generates all potential edges or ducts in the graph. Similar to the nodes, the ducts are characterized by a set of parameters such as a roughness coefficient, a start and end node, a length (i.e., the Euclidean distance between the start and end node) and a maximum (hydraulic) diameter. The last parameter implies that all smaller duct sizes can be installed as well at this location. Since supply air ducts are subjected...
Table 3: Classification of indoor air quality or IAQ (typical range of outdoor air for a non-smoking area)

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Rate of outdoor air (m³/h/person)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IDA 1</td>
<td>High IAQ</td>
<td>&gt; 54</td>
</tr>
<tr>
<td>IDA 2</td>
<td>Medium IAQ</td>
<td>36 - 54</td>
</tr>
<tr>
<td>IDA 3</td>
<td>Moderate IAQ</td>
<td>22 - 36</td>
</tr>
<tr>
<td>IDA 4</td>
<td>Low IAQ</td>
<td>&lt; 22</td>
</tr>
</tbody>
</table>

to a telescopic constraint, i.e., the diameter of an upstream duct must not been less than the diameter of a downstream duct, the size of the set of potential ducts will reduce when going downstream in the system.

4.3.1. Generation of Main Ducts
First, ducts are created which connect the shafts with the centralized supply node and the corresponding secondary supply nodes. Moreover the shafts and secondary fans are connected mutually as well. As mentioned before, the maximum diameter of these ducts is determined by the dimensions of the shafts in the building.

4.3.2. Generation of Ducts in the Zones

• Hallway ducts
  For every set of hallway nodes generated, a minimum spanning tree, connecting all hallway nodes associated with one fan, is drawn, using Prim’s algorithm. The begin-nodes and end-nodes of the edges or ducts are assigned to these edges while drawing the spanning tree. The edge weights or duct lengths equal the Euclidean distances between the begin-nodes and end-nodes.

• Room ducts
  All demand nodes within a room are connected by triangulation. The begin-node, end-node and length of each duct are defined by the triangulation itself. The maximum diameter of the ducts, however, depends on the room type as every room type has a different demand (table 2).

From the benchmark instances generated by our test network generator and described in this section, different ADN layouts can relatively easy be
generated (e.g., with a spanning tree). The layouts may not be optimal, but could be useful to compare and evaluate the performance of existing duct design methods, that are limited to the duct (and fan) sizing. However, this is of course not desirable, since the layout is then considered again as an independent variable. The aim of our test network generator, is to foster future research, where the layout and duct and fan sizing are seen as interrelated decision variables that should be optimized simultaneously.

5. Conclusion and future research

5.1. Conclusion
This paper highlights two main shortcomings in existing research. First, current design methods are limited to (the optimization of) duct (and fan) sizing without taking the layout into account. Second, benchmark instances are lacking and thus the performance of existing duct design (optimization) methods cannot be evaluated and compared properly. As a result, different design methods are used in practice, where each design engineer uses his own rules of thumb and experiences. The layout is largely designed manually, resulting in designs that are workable but not necessary optimal. An objective comparison between different designs is very difficult. Moreover, current design methods cannot respond quickly to external changes during the design phase.

In this research, we address these shortcomings, by proposing a test network generator that is able to generate realistic benchmark instances. By integrating user input into the network generator, instances of varying characteristics can be generated. On the one hand, the instances can be used to compare existing duct design methods. On the other hand they can be used to foster the development of a novel design method that optimizes both the layout and duct and fan sizing. It is clear that design engineers would benefit from such a method which will lead to better quality and more flexible designs. The foundations for such a method are established in section 3 by formulating the novel optimization problem as a non-linear combinatorial optimization problem, which can best be solved by metaheuristic optimization techniques.

5.2. Future research
As stated in section 3, the formulation of the ADND optimization problem is currently simplified to a network optimization problem with a single objective
function. The short term aim of this research is to develop an optimization algorithm that is able to solve this novel optimization problem. Since the design of air distribution systems depends strongly on the requirements of the end user, the long term aim of this research is to represent the ADND optimization problem as a multi-objective optimization problem with the minimization of the life cycle cost, energy consumption and initial material cost as conflicting objective functions. As an example of the conflicting nature of these objectives consider, for example, that a larger cross-section of the ductwork induces higher material costs, but lower energy consumption. A Pareto-set of non-dominated solutions will be generated by the optimization algorithm and it is up to the decision taker to make a trade-off between the different solutions.

6. References


Figure 5: generation of shafts on the left (red) and supply nodes on the right (green)

Figure 6: generation of hallway nodes on the left (black) and room nodes on the right (purple = small office, orange = meeting room, light green = open office, dark green = cafeteria)
Figure 7: Generation of main ducts (central fan-shaft (red continuous), shaft-shaft (red dotted), fan-fan and shaft-fan (green))

Figure 8: Generation of hallway ducts on the left (thick grey line) and room ducts on the right (thin grey line)