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Reference:
Kabbara Zakarya, Jorens Sandy, Seuntjens Oskar, Verhaert Ivan.- Simulation-based optimization method for retrofitting HVAC ductwork design
Energy and buildings - ISSN 1872-6178 - 307(2024), 113991
Full text (Publisher's DOI): https://doi.org/10.1016/J.ENBUILD.2024.113991
To cite this reference: https://hdl.handle.net/10067/2032060151162165141

Simulation-Based Optimization Method for Retrofitting HVAC Ductwork Design

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Abstract

Retrofitting the design of a ductwork system is often a critical aspect when renovating a centralized air distribution system. However, the existing approaches rely on the rules of thumb due to the absence of a standardized guideline for the design retrofitting process. Consequently, design engineers face costly and time-consuming challenges in generating retrofitted designs, particularly when dealing with the complexities of reusing the existing ductwork system. Although their design output may achieve functionality, it is not necessarily optimal in terms of cost and performance. To overcome these challenges, this paper proposes a simulation-based ductwork design strategy that utilizes metaheuristic optimization techniques to generate optimized ductwork designs for retrofits. The proposed method offers an automated solution for generating optimized ductwork configurations (i.e., layout and sizes). It strategically maximizes the reuse of existing ductwork components while simultaneously fulfilling the design performance criteria desired by the system and minimizing its life cycle cost. A case study was conducted to present the effectiveness of the developed method in retrofitting the ductwork design for a multi-storey school building. This study involved a comparison between the design solution generated by the proposed method and the design solution generated through a conventional retrofitting design approach. The results from the proposed design retrofitting method showed a 17% lower LCC and an approximately equally well-balanced design. These findings indicate the method's promising potential to contribute to the HVAC industry by providing an effective simulation-based method for automatically optimizing ductwork designs for retrofits.

1. Introduction

1.1. Overview

In the world of heating, ventilation, and air conditioning (HVAC), retrofitting ductwork systems has a crucial role in optimizing the building performance and energy efficiency. Many existing buildings still rely on outdated and inefficient ductwork systems. These inefficient systems can be subjected to poor air distribution, increased energy usage, and balancing and control problems, all of which can harm the indoor air quality (IAQ), and radiate noise issues [1]. Retrofitting the design for these systems presents a promising opportunity to enhance energy efficiency, reduce operational costs, and improve indoor environmental quality (IEQ). The process entails adapting the ductwork layout and sizes, and changing or adding other ductwork components (e.g., silencers and pressure valves) in order to address the system's inefficiencies and optimize its performance. Moreover, ductwork retrofitting enables the incorporation of advanced ventilation strategies, including demand-controlled ventilation (DCV) and hybrid ventilation control, assuring ideal IAQ and fostering a healthier living or working environment [2], [3].

Additionally, when a building's usage or occupancy changes, retrofitting its ductwork design often becomes necessary. In other words, when buildings are renovated (or repurposed), the HVAC requirements typically require modifications to align with the adjusted functionalities. In this regard, retrofitting the ductwork ensures that the HVAC system can satisfy the specific demands of the new occupancy. Whether it involves transforming a school building into an office space or converting an industrial facility into a warehouse, retrofitting the ductwork accommodates the changing airflow dynamics and demands while maximizing the reuse of the existing materials to align with the circular economy and minimize the design-associated costs [4], [5], [6].

1.2. Problem formulation: ductwork design retrofitting problem

Generally, the design of ductwork for new systems and retrofits are challenging processes that have to be accomplished within a limited budget and time [7]. The challenges arise due to the long list of indicators that must be fulfilled by the system. This includes achieving the desired Indoor Air Quality (IAQ), acoustical and hygrothermal comfort, minimal energy usage, and cost-effective investment. Unfortunately, there is no commonly known standardized guideline that is capable of optimally fulfilling all these indicators. Therefore, engineers still rely on their rules of thumb and experiences to generate workable designs, yet not necessarily optimal ones [8], [9], [10].

Whether for new systems or retrofits, the ductwork design is a technical and professional process guided by common standards recommendations, such as those provided by ASHRAE and ACCA Manual D [11], [12]. While these standards may offer valuable guidance, it is important to recognize their limitations. The design considerations rely on simplified assumptions for ductwork design, such as fixed velocity limits or uniform pressure losses [13]. Yet, these assumptions may not fully consider the project-specific requirements, resulting in suboptimal ductwork configurations and inefficiencies. Also, there are no guidelines for an optimal ductwork layout, while many research studies stress its significant impact on the system's performance and cost [9], [10], [14], [15]. Moreover, the ductwork design does not consider variable occupant behavior in the design process. However, many buildings often operate for a large portion of the year at off-peak flow levels due to the variable demand conditions [10], [16]. Therefore, designing an air distribution system without accounting for the load variations in every zone may not lead to optimal designs. Additionally, space limitations due to the building architecture can pose challenges to achieving optimal ductwork design, requiring additional customization and expertise.

In this regard, many research efforts have been dedicated to designing and optimizing ductwork systems [16], [17], [18], [19]. The primary focus of these methods is to optimize ductwork sizes to reduce the system's Life Cycle Cost (LCC). Using LCC as an optimization objective is advantageous because it finds a balance between operational and capital expenses, ensuring the system is cost-effective and efficiently utilizes resources throughout its lifespan. Jorens et al. critically reviewed some of these methods and identified several limitations, including their complexity for users, lack of practical applicability, absence of benchmark instances (meaning the methods were tested on small, non-representative cases), and neglect of the potential benefits of optimizing the ductwork system's layout and sizes simultaneously [20]. From there, they proposed the Air Distribution Network Design (ADND) optimization method, which employs a heuristic algorithm to automatically generate various layouts and sizes for air distribution ductwork in buildings, aiming to minimize ductwork material costs. This method revealed the significant impact of layout design on material costs. Despite acknowledging the need to consider layout and sizes concurrently, the ADND method has limitations, such as assuming constant friction losses in ducts and overlooking the impact of fittings' pressure losses, which are crucial for ductwork design and efficiency. Other studies have recognized the importance of optimizing layout, but overlook treating layout and sizes as interconnected optimization factors, thus not fully exploiting the design's optimization potential. To address these shortcomings, Kabbara et al. [10] recently introduced a simulation-based ductwork design optimization method that optimizes both ductwork layout and sizes, aiming to minimize the system's LCC.

However, all these methods mainly focus on optimizing ductwork design for new systems, not retrofits and their additional associated challenges. Yet, the necessity for retrofitting HVAC ductworks has grown considerably, compelled by the need to improve indoor air quality, mitigate energy wastage, and secure the health and well-being of occupants (especially within and after the COVID-19 crisis) [21], [22], [23], [24]. Despite these pressing needs, there appears to be a gap in the literature regarding a comprehensive methodology for the optimal redesign of ductwork (layout and sizing) specifically tailored for retrofitting purposes. In the context of retrofitting ductwork designs, the challenge of identifying which parts of the existing system can be efficiently reused exceeds that of designing new systems. With the absence of established guidelines for determining the reuse viability, retrofitting requires a strategic approach that integrates with the building's existing structures and components. A thorough investigation of the current ductwork becomes essential to understand its capabilities and limitations, ensuring that the retrofitting process can effectively enhance and optimize the system's design. This preliminary evaluation is crucial for informing decisions and achieving an efficient retrofit.

When evaluating the existing system, the alignment of existing duct sizes with the newly demanded airflow requirements is a critical consideration. If the current duct sizes are insufficient, it becomes necessary to plan for changing or resizing the ducts. Conversely, even if the existing sizes meet the airflow requirements, they may not necessarily be the most suitable size for the retrofitted system. It is important to note that while reusing existing ductwork materials may initially seem economically advantageous (i.e., materially), it can introduce trade-offs in terms of energy consumption, particularly related to fan operation. To be more specific, the original duct sizes might have been designed to accommodate a different airflow capacity than what the retrofit requires, potentially resulting in increased air resistance (pressure drops) and consequently, higher energy demands from the system's fans. This increase in air resistance may necessitate the fans to work at a higher power to maintain the desired airflow, leading to increased energy consumption. Furthermore, the change in air resistance may also impact the pressure balancing of the retrofitted design, potentially causing unbalanced airflow distribution within the ventilation zones. This pressure imbalance can result in uncomfortable hot and cold spots, drafts, and temperature variations throughout the building, undermining the overall effectiveness of the ventilation system and compromising both comfort and energy efficiency. Therefore, while the cost savings associated with material reuse might seem beneficial, it is crucial to assess and consider the potential consequences on fan energy consumption and system balance when choosing to reuse existing ductwork materials. Having the right balance between material cost, energy efficiency, and system performance is essential for making well-informed decisions in the retrofitting process.

Moreover, by consideration of existing ductwork complexity is increased by the need to align also with the architectural constraints of the retrofitted system. Ducts must function optimally while integrating aesthetically, considering space use, visual appeal, and structure.

Nevertheless, evaluating the existing ductwork system can be a time and resource-intensive process, even with the available modelling tools. In light of this challenge, it is important to note that engineers, faced with time and resource constraints and the absence of a standardized retrofitting approach, may opt for a more expedient approach. This approach involves the complete dismantling of the existing system and the creation of a completely new design from scratch, driven by the need for a faster and easier retrofitting solution. While this expedited approach may offer a quicker design solution for implementation, it carries the risk of overlooking opportunities to reuse existing resources. This missed opportunity can lead to excessive expenses and resource consumption.

Overall, the limitations of the ductwork retrofitting process underscore the need for a holistic approach driven by optimization to satisfy the system's variable indicators efficiently. Such a holistic approach should aid design engineers with a detailed assessment of the existing system to systematically design the new retrofitted system while comprehensively considering the critical design factors.

2. Aims and Objectives

Considering the complexities of ductwork design for retrofits, this paper aims to propose a basic strategy for a holistic simulation-based method driven by optimization. The method seeks to assist engineers in the ductwork design process for retrofitted systems by automating it and optimizing the performance and cost of the retrofitted design, thus addressing the laborious and resource-intensive tasks

The goal of the method is to be able to strategically make duct layout and sizing decisions for the retrofitted system, considering the following comprehensive set of objectives simultaneously:

- **Assessing the existing ductwork system:** The proposed optimization method should be able to evaluate the cost (i.e., fan energy, ductwork material and installation costs) and the performance (e.g., pressure drops and airflow velocity) of the existing ductwork system for potential re-use in the retrofitted design.
- **Fulfilling performance criteria as desired by the retrofitted system:** While reusing (parts of) the existing ductwork may yield cost benefits, it also poses challenges such as pressure balancing issues and potential impacts on overall system performance and fan energy. These challenges have to be addressed in order to fulfil the performance criteria as desired by the retrofitted design.
- **Fulfilling the desired optimization objective function:** the optimization objective function for the ductwork design retrofitting problem is minimizing the life cycle cost (LCC). The reason for choosing this objective function is motivated in section 3.2.

3. The retrofitting design strategy

The proposed retrofitting method builds on the recently developed method by Kabbara et al. [10], which elaborates on the basic work of Jorens et al. [9] for designing ductwork systems for new buildings. Their approach offers advantages in terms of having a computational-friendly simulation-based design method driven by metaheuristic optimization to minimize the ductwork's LCCs. The significance of using metaheuristics optimization techniques, both for new buildings and retrofits, lies in its flexibility in considering different design constraints (e.g., architectural constraints due to space limitations and velocity constraints to limit noise levels), and handling conflicting decision variables. Using metaheuristics also aims to achieve optimized solutions that fit into each project's requirements.

Our research innovation lies in the extension and adaptation of this methodology, specifically tailored to the context of retrofitting projects. The proposed approach strategically incorporates the existing ductwork systems within the retrofitting design process. The strategic design decision to include (parts of) the existing ductwork is guided by a performance assessment of the pre-existing systems. This addresses the complexities associated with integrating the existing ductwork system and maximizes its reuse whenever convenient. While addressing these challenges, our method aims to preserve all the advantages previously mentioned for designing new systems. Additionally, and similarly to designing new systems, the retrofitting method is also developed with the design optimization objective of minimizing the LCC.

3.1. Background: ductwork design optimization algorithm for new buildings

The idea behind the ductwork design optimization method, for new buildings, was initially laid out by Jorens et al. [25] to optimize the ductwork configuration (i.e., ductwork layouts and sizes) while minimizing the ductwork material costs for new systems. Recently, Kabbara et al. [10] improved the method to optimize ductwork configurations while minimizing the ductwork LCC, i.e., fan energy, material, and installation costs. Additionally, the latest efforts leveraged the optimization approach by incorporating supplementary insights (e.g., enhanced consideration of fittings at an early design stage [13]) and thus upgrading the overall performance and cost of the system.

An overview of the latest ductwork optimization method is summarized in Figure 1. The method automatically generates numerous ductwork design configurations while optimizing them. It starts from a building's floor plan, where all air openings with the corresponding design airflow rates are manually indicated, as well as all the potential duct and fan locations (as an example, see Figure 7). The intended floor plan is represented using graph theory, as a rooted undirected weighted graph G(N, E), where E is the set of edges representing potential air ducts and N is the set of nodes or vertices indicating possible root nodes (fans), joints (i.e., fittings), and demand nodes. An example of the undirected weighted graph is represented in Figure 7. The method is also subjected to additional constraints, such as maximum duct heights, maximum air velocities, and maximum fan pressure. Local standards, client preferences, and architectural restrictions determine these constraints. These constraints ensure the practical feasibility of the generated design. They are given as inputs to the design method.

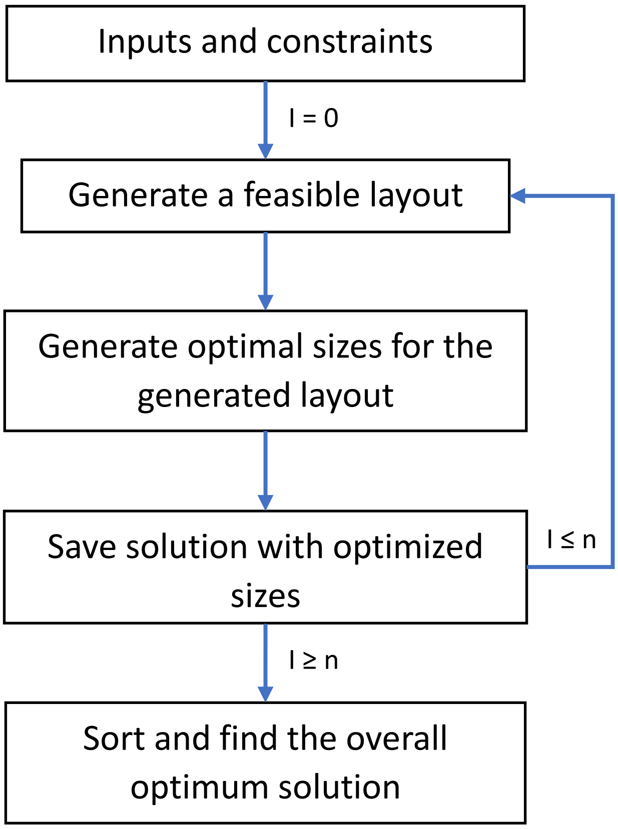

Figure 1: design optimization method for new ductwork systems. N is the number of generated layouts specified by the user

The design method consists of two (iterative) main phases, i.e., generating the layout and sizing the generated layout. In the first phase, a ductwork layout configuration is generated from scratch and evaluated for feasibility. A feasible layout can be seen as a directed tree, without loops, that connects the root node (i.e., fan) to all demand nodes (i.e., air openings) in the graph. Following the generation of the layout, the second phase starts by optimizing the duct sizes for every feasible layout with the objective of minimizing the system's LCCs. Both local search and constructive metaheuristic techniques are employed to optimize the ductwork sizes. The look-ahead strategy was adopted as a decision-making search strategy for the constructive heuristic to size the critical paths in the system. The critical paths are paths with the highest total pressure drop in the system, which influence the fan energy usage. This strategy aims to predict the impact of different possible choices (i.e., duct-section sizes) by assessing them and then selecting the one leading to the best possible outcome (i.e., the one having minimal LCC). Local search, particularly the mildest-ascent strategy, was utilized for optimizing the sizes in non-critical paths. This entails the move strategy iteratively improving the solution while applying incremental variations to it until no further improvements (i.e., minimizing LCC) can be attained.

After sizing the generated layout, the design of the ductwork configuration is finalized and saved as a local optimum solution. The design method is then repeated until sufficient solutions are generated and saved. The top solution (i.e., the solution with the lowest LCC) is considered the optimal solution for this optimization problem.

3.2. Ductwork design optimization objective functions for retrofits: Minimizing LCC

For retrofitting ductwork design, incorporating the reduction of the system's LCC is a captivating optimization objective function. Retrofitting projects involve modifying existing systems to improve their (re)utilization, performance, and energy efficiency. Thereby, the LCC provides a systematic and comprehensive evaluation of the cost implications associated with these modifications throughout the retrofit's entire life cycle. By considering these economic factors, LCC provides insights into the financial feasibility of different retrofitting options, guiding decision-making towards cost-effective designs that minimize the LCC.

The mathematical representation of LCC minimization is adopted from Kabbara et al. [10] and adapted to fit our design retrofitting problem. The LCC includes the ductwork material, installation, and fan energy costs over the life cycle. It is expressed as follows:

$$LCC = E_p . PWEF + \sum_{d\epsilon D} \sum_{t_d \epsilon T} X_{td} C_{td} L_d + \sum_{o\epsilon O} \sum_{s\epsilon S} X_{os}\, C_{os} - \sum_{d\epsilon D} \sum_{t_d \epsilon T} Y_{td} C_{td} L_d - \sum_{o\epsilon O} \sum_{s\epsilon S} Y_{os}\, C_{os} \qquad \textit{Equation 1}$$

The first term in the equation represents the fan energy cost (Euros), where Ep is the annual energy cost, estimated using Equation 2. PWEF is the present worth escalation factor, estimated using Equation 3. X_{td} is a binary decision variable that indicates whether the selected duct d is of type t ($X_{td} = 1$) or not ($X_{td} = 0$). Additionally, if the duct section already exists in the old system and is intended to be reused in the retrofitted system, X_{td} is assumed to be zero. L_d is the duct length. Similarly to duct sections, X_{os} equals 1 when the air opening of size s and type o is selected, and 0 when an air opening of type s is not selected or if the diffuser already exists in the old system and intended to be reused in the retrofitted system. Y_{td} and Y_{os} are two binary decision variables for ducts and air openings, respectively. They indicate whether the existing duct (of size d and type t) or air opening (of size s and type o) in the existing system is reused (Y_{td}=0 or $Y_{os} = 0$) or not (Y_{td}= 1 or Y_{os}=1). C_{td} and C_{os} are the corresponding costs to the ducts and air openings based on their size and stage (e.g., new or old).

$$E_p = \frac{1}{10^3 \eta_m} \sum_{g}^{G} \frac{Q_{fan,g} . P_{fan,g} . (E_d + E_{c,g} . \psi_g T)}{\eta_{shaft,g}} \qquad \textit{Equation 2}$$

With,

- *$E_{c,g}$ is the present cost of energy at operation mode g [Euros/KWh]*
- *E_d is the energy demand cost [Euros/KW]*
- *ψ_g is the fraction of time system operates in mode g*
- *T is the operation time [hours/year]*
- *η_m being the motor efficiency of the fan [dimensionless]*

- *G is the operation mode*
- $\eta_{shaft,g}$ *is the shaft efficiency at operation mode g [dimensionless]*
- $Q_{fan,g}$ *is the total demand airflow rate at operation mode g [m³/s]*
- $P_{fan,g}$ *is the fan's total pressure [Pa]*

$$PWEF = \begin{cases} \dfrac{[\frac{1+J}{1+I}]^{a} - 1}{1 - [\frac{1+I}{1+J}]} & if \ \ I \neq J \\ a & if \ I = J \end{cases} \qquad \text{Equation 3}$$

Where,

- *J is the escalation rate per year [dimensionless]*
- *I is the annual interest rate [dimensionless]*
- *a is the amortization period [years]*

It is crucial to underscore that the fan energy cost is evaluated based on the pressure drops generated from ducts (i.e., rectangular and circular), fittings (i.e., Tee, bends, and transitions), and diffusers in the ductwork system. The pressure drops due to the other components that can occur in the system (e.g., balancing valves and reheating coils) are not considered, as we don't size these components at this stage.

3.3. Models

To evaluate the system's aeraulic performance and costs, it is crucial to use models that are capable of accomplishing this task. These models serve as the basis for implementing the method effectively. These models were implemented in Python coding language.

3.3.1. Aeraulic models

The aeraulic models estimate the pressure drops in components of the air distribution systems (i.e., ducts, fittings, and diffusers).

The pressure drop generated from ducts is estimated using Equation 4

$$\Delta p = f \frac{L}{D_H} \rho \frac{v^2}{2} \qquad \text{Equation 4}$$

- *f is the friction factor*
- *L [m] is the length of the duct*
- *v [m/s] is the air velocity*
- D_H *[m] is the hydraulic diameter*

The friction factor *f* is estimated using the Cole-Brook White equation [1] (Equation 5)

$$\frac{1}{\sqrt{f}} = -2 \ log \ (\frac{\epsilon}{3.7 D_H} + \frac{2.51}{Re\sqrt{f}}) \qquad \text{Equation 5}$$

- ϵ *[m] is the roughness of the duct*
- *Re is Reynold's number, estimated using* Equation 6 *.*
- ρ *[Kg/m³] is the air density*

$$Re = \frac{\rho v D}{\mu} \qquad \text{Equation 6}$$

- μ *[dimensionless] is the fluid viscosity*

For fittings, the pressure drop can be estimated using Equation 7

$$\Delta p = \rho \zeta \frac{v^2}{2}$$ *Equation 7*

- *ζ is the pressure loss coefficient for fitting*

ζ- values are looked up in the duct fitting database of ASHRAE [26] depending on their type.

3.3.2. Cost models

The cost models used for this research are adopted from Kabbara et al. [10].They are based on ductwork material and installation prices that are averaged according to Belgian design firms. The developed simulation-based method can automatically assign the price for every component by giving its dimensions. The circular ducts' costs are presented in Appendix E. Whereas the rectangular ducts' costs are averaged to 62 €/m^2.

Acknowledging the potential variability in cost structures across different countries, these cost models offer a starting point for cost analysis for the method, providing a localized perspective. However, users can have different cost models that can be easily adapted to fit the method based on their unique economic regions.

3.4. Design inputs and constraints

Before delving into our proposed retrofitting method, it is important to establish a clear understanding of the inputs involved. Retrofitting ductwork design necessitates adapted and additional inputs compared to new systems. The inputs required for ductwork design retrofitting can be summarized as follows:

1. **Retrofitting floor plan:** The retrofitting floor plan shows the new layout of the building, as well as the positions of the air openings and the associated desired nominal flow rates. As an example, the retrofitting floor plan input is illustrated in Figure 4, Figure 5, and Figure 6. Figure 4 showcases the original floor plan of the system, whereas Figure 5 and Figure 6 present the renovated version. In these figures, notable changes include the addition and removal of walls, resulting in larger rooms and an enhanced overall layout.
2. **The existing HVAC Design:** This input offers information about the layout and sizing of the existing ducts. An example of the existing ductwork design and its sizes is presented in Figure 4 and Appendix A.
3. **All the new potential ducts for the retrofitted system (and the new fan position):** This includes information about all potential ducts that may be chosen for the final retrofitted solution. It is regarded as an undirected weighted graph, where the fan is the root node and ducts are the weighted edges (similarly to the approach for new systems). All the potential ducts have beginning and end nodes, which are represented by numbers. An example of all the potential ducts is represented in Figure 7.
4. **New flow rates per operation mode**: Given that most of the modern systems are demand-controlled ventilation systems, it is important to consider flow rates for different operation modes. Consequently, the system's operation can be optimized to accommodate to these variations effectively.

In addition to the above inputs, the design method is also bounded by the following constraints:

1. **Kirchhoff's Law:** For this study, the ductwork system obeys Kirchhoff's law. This implies that the inlet flow is equal to the outlet flow, assuming no leakage in the system.

2. **Pressure balance:** The pressure drops for all paths are the same. This is to attain the demanded ventilation rates. This is a boundary condition for a well-performed ductwork design. We aim to adhere to this boundary condition as closely as possible while sizing the duct sections. However, violating this condition does not eliminate the solution, as it can be treated by adding pressure valves.
3. **Standard duct sizes:** The available standard sizes that are commercially available are used to discretize the duct sizes.
4. **Space restrictions:** The space restrictions imposed by the floorplan architecture. Accordingly, the ducts can be correctly sized and routed to fit within the designated space by being aware of the architectural restrictions.
5. **Velocity restrictions:** choosing an appropriate airflow velocity is essential for the system's performance as it may affect the radiated noises from the system and indoor comfort.

3.5. Ductwork design retrofitting method

The design retrofitting simulation-based method establishes a basic framework by offering an organized and systematic way to deal with the difficulties involved. The proposed method generates various ductwork design configurations while considering existing ductwork components within the solution for assessment.

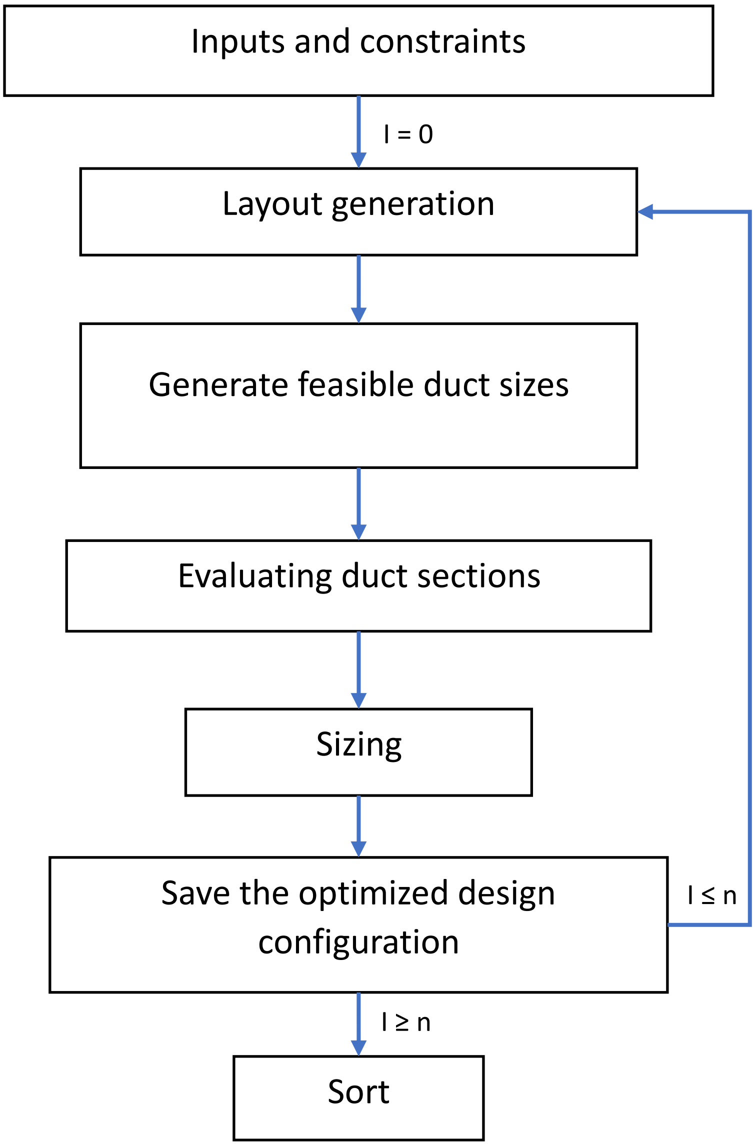

Figure 2: retrofitting method, N is the number of generated layouts specified by the user

The method steps are summarized in Figure 2 and described as follows:

1. **Inputs and constraints:** The method is initially supplied with inputs and the constraints presented in Section 3.4.
2. **Layout generation:** A layout is generated for the retrofitted floor plan, assuming the ductwork design of the existing system does not exist (assuming the design is for a new system). The generation of the layout is adopted from Jorens et al. [9]
3. **Generating duct sizes:** Following the layout generation, a pool of all possible sizes for all the duct section sizes for the layout is generated. The sizes are generated according to the imposed constraints (i.e., velocity, height restrictions for the duct section, and the standard duct sizes) and the nominal flow rate. The ducts are sized using Equation 8.

$$A = \frac{Q}{v}$$ *Equation 8*

With,

- A is the duct cross-sectional area [m^2]
- Q is the airflow rate [m^3/s]

4. **Evaluating duct sections:** Evaluating the duct sections enables the design method to make informed decisions concerning duct design optimization.
   An example illustrating the evaluation process is presented in Figure 3. In this example, duct-sections 1, 2, and 3 were already existing in the system, each with 5m length and diameter sizes of 355 mm, 200mm, and 315 mm, respectively. However, the demand airflows have changed to the ones presented in the figure. Consequently, the system may necessitate retrofitting.

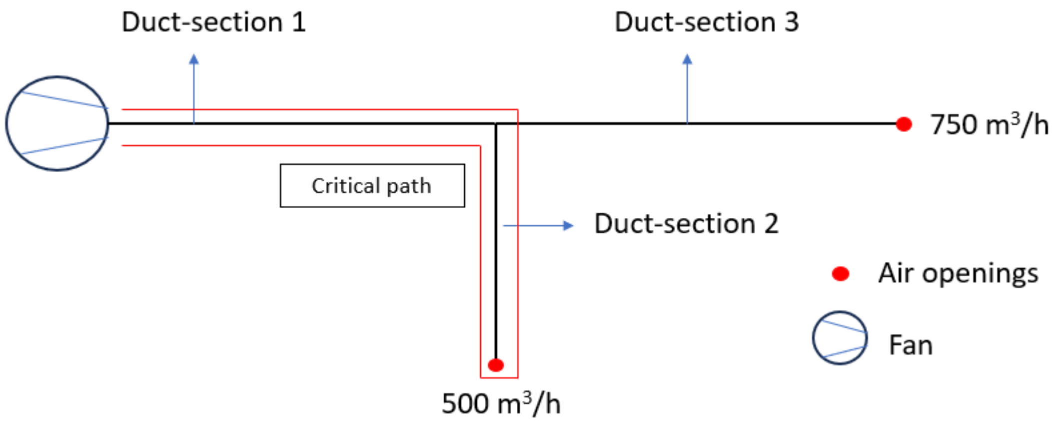

Figure 3: Ductwork simplified example

The evaluation process involves assessing their pressure drops, and associated costs. Table 1 presents the duct sizes, pressure drops, and associated costs of the duct system in Figure 3. The associated costs include the investment and the fan energy cost caused by the ductwork system. The total fan energy usage can be estimated after assessing the fan energy usage due to every duct-section using.

The total fan energy cost can later be assessed using Equation 2. $P_{fan,g}$ is the fan's total pressure (only due to ducts and fittings) which is also equivalent to the summation of the pressure drops for each duct section in the critical path. In the case of the ductwork example in Figure 3, duct-sections 1 and 2 are in the critical path, whereas duct-section 3 is not. Therefore, the energy consumption from duct-section 3 is assumed to be zero (see Table 1).

It should be noted that if the duct section sizes can be found in the existing ductwork system, its material cost is zeroed. For the example in Figure 3, duct-sections 1, 2 and 3 already existed with sizes 355 mm, 200 mm and 315 mm, respectively. Consequently, by referring to Table 1, the material costs associated with these specific sizes of duct sections are considered zero.

Note: for this paper, the method assumes the absence of damaged duct sections, leading to the pricing of new duct installations if needed.

*Table 1: Duct-section evaluation. *Duct section size already in the existing system*

Duct section	sizes (mm)	Pressure drops (Pa)	Energy (Kwh)	Material cost (€)	Energy cost (€)	LCC (€)
1	400	1.6	162.2	375	64.9	439.9
	355*	2	202.8	**0***	81.1	81.1
	315	3.2	324.4	275	129.8	404.8
2	250	7.5	760.4	250	304.2	554.2
	200*	13.8	1400	**0***	559.7	559.7
3	**315***	1.3	0	**0***	0	0
	250	3.9	0	250	0	250

5. **Sizing:** After evaluating all the duct section sizes for the generated layout, we start sizing the duct sections. We also start by sizing critical paths and then the non-critical paths, as advised by the method for new systems [13] Sizing the duct sections also depends on the design optimization objective (input 5, section 3.4)
    i. Starting with the critical paths, we start sizing their duct sections. This is achieved by employing constructive heuristic optimization, namely the look-ahead optimization strategy. This implies picking the sizes having the lowest LCC for every duct section. For the critical paths, the LCC includes the fan energy and ductwork material costs, as previously assessed in Step 4. In this regard, the algorithm would favor reusing the duct sections that are feasible to be reused in the new system since they are more likely to have lower LCC, as their ductwork material cost are zeroed. For the example in Figure 3, the evaluation of duct sizes can be found in Table 1. The look-ahead method can easily find the duct sizes by selecting the duct size with the lowest LCC. In the case of duct-section 1, the method favored reusing the existing duct size of 355mm, as it has the lowest LCC. However, for duct-section 2, the algorithm did not favor reusing the existing size of 200mm due to its high energy cost, which results in an increased LCC, despite having a material cost of zero. For this duct section, the algorithm favored selecting the size with the lowest LCC, which is 250mm (see Table 1)
    ii. After sizing the critical paths, their total pressure drops for every operation mode can be known, and sizing duct-section in the non-critical paths can begin. These duct-sections are exclusive of those shared with the critical path. For the example in Figure 3, the only duct suction that would undergo sizing at this stage is duct-section 3.

        The local search heuristic optimization technique, namely the mildest-ascent strategy, is utilized for this process. Initially, we start considering the duct section size with the smallest LCC. Therefore, for the example in Figure 3, the initial duct-section 3 size is 315 mm, as it has the lowest LCC (see Table 1).

        Once the initial sizes of the noncritical path are accomplished, the total pressure drops for these paths are assessed. Paths having total pressure drops higher than the total pressure drop at the critical paths undergo the mildest-ascent optimization. This means that, for these non-critical paths, the algorithm will be iteratively looking for the duct section having the lowest impact on increasing the ductwork material cost (which is also the LCC for non-critical paths, as their pressure drops do not affect the energy costs) while increasing its size to decrease the pressure drop in the path. Once found, the duct section size is increased. The iterations continue until the total pressure drop in the path is less than or equal to the total pressure drop at the critical path. By adopting this approach, we also prioritize the reuse of old duct sections, as their ductwork material cost has already been zeroed, thus having a low LCC. Consequently, the algorithm favors retaining the duct section reusability.

        In the example in Figure 3, the pressure drop at the critical path (duct-section 1 + duct-section 2) with the chosen sizes in (i) is 9.5 Pa. For the non-critical path (duct-section 1 + duct-section 3) the pressure drop is 3.3 Pa, which is less than the pressure drop at the critical path. Therefore, there is no need for the mildest-ascent process for this case and the duct section 3 size can remain 315 mm.

6. **Save and sort:** The design solution is completed once the sizing process is finished. The LCC is assessed again for the completed solution. From there, the solution is saved as a local optimum solution. The process from 2 to 5 is repeated until enough solutions are generated. Finally, the solutions are sorted based on their LCC, and accordingly, the top solution is considered to be the global optimum solution.

4. Case study: method demonstration

When comparing our developed retrofitting method with conventional approaches, establishing a benchmark can be challenging due to the absence of a standard method. Design engineers often face two primary approaches for retrofitting: one that fully dismantles the existing system and redesigns it from scratch and another that aims to reuse parts of the existing system. This variability in conventional methods leads to diverse ductwork design configurations for the same floor plan, making it difficult to establish a standardized comparison. Specifically, when using conventional methods that particularly aim to reuse parts of the existing system, individual design engineers may adopt different approaches, resulting in distinct ductwork design configurations. It is also challenging to determine which parts of the existing ductwork would be retained in the retrofitted design configuration. This diversity among designs poses a significant challenge in establishing the conventional design method as a consistent benchmark for comparison with our proposed approach. Consequently, for this research, we conducted a qualitative comparison only between our developed design approach and the conventional approach that focuses on reusing the existing system (see section 4.3.3).

Nevertheless, for this case study, we chose to compare the outcomes of our proposed method with the conventional approach of completely dismantling the existing system and undertaking a complete redesign. This conventional approach serves as a suitable benchmark for comparison because it involves no reuse of the existing ductwork, providing a clear contrast to our method, which strategically incorporates the existing ductwork system. Our goal is to achieve two primary objectives. Firstly, we seek to demonstrate the effectiveness of our proposed method in strategically reusing the existing ductwork design for retrofitting, thereby achieving a cost-efficient and well-performed system. Secondly, we aim to conduct a comparative analysis between our retrofitting design approach and the conventional method of complete ductwork dismantling and the creation of an entirely new design, without reusing any of the existing system. Hereby, we seek to determine whether it is worthwhile to opt for a full dismantling or to focus on maximizing the reuse of the existing system. For generating a completely new design, we have chosen to employ the optimization method developed by Kabbara et al [10]. This method has been selected as its design optimization objective is also to minimize the system's LCC, similarly to the proposed retrofitting method.

In addition to assessing cost considerations, our study also aims to evaluate the feasibility of achieving a balanced design while reusing the existing duct systems through our approach. Balanced ductwork design plays a crucial role in achieving a well-performed and efficient system, promoting high IEQ through maintaining healthy IAQ (by ensuring even flow distribution), and securing acoustical comfort (by mitigating the reliance of the pressure balancing valves). To assess the balancing criteria of the designed system, we adopted the approach, in [13], to assess the mean balancing percentage for every generated design. The mean balancing percentage is expressed as follows:

$$Mean\ balancing\ \% = \frac{\sum_{n=1}^{n=N} Balancing\ \%\ in\ path\ n}{N} \qquad \textit{Equation 9}$$

$$Balancing\ \% = \frac{Pressure\ drop\ in\ the\ path}{Pressure\ drop\ at\ critical\ path} \times 100 \qquad \textit{Equation 10}$$

With n representing a non-critical path and N representing the total number of non-critical paths

The Mean Balancing % and the Balancing % for each path should be as high as possible in order to generate more balanced systems. Consider a path with a low Balancing %. In that case, a balancing damper is required to generate an increased pressure drop in the path with pressure drop deficiencies (i.e., path pressure drop crucial path's pressure drop).

4.1. Case description

In pursuit of the case study's objective, we applied the two methods on two floors of a multi-story school building. The two floors were initially made up of identical small-sized classrooms with 24 demand nodes (12 air openings per floor) with the same design airflow rate per opening, as presented in Figure 4. Initially, each floor supplies an airflow of 5280 m^3/h with a total fan flow of 10560 m^3/h. The fan is located on the roof and conveys the conditioned air to the two floors through the ducts in the shaft. However, each floor usage was repurposed with changing room sizes and design loads. As presented in Figure 5 and Figure 6, the allocation of air openings, floor division, and airflow rates was minorly adjusted in the second floor (maintaining the floor's total design airflow rate of 5280 m^3/h) and majorly adjusted in the 1st (decreasing the floor's total design airflow rate to 3962 m^3/h). Thus, this change would require retrofitting the existing ductwork system.

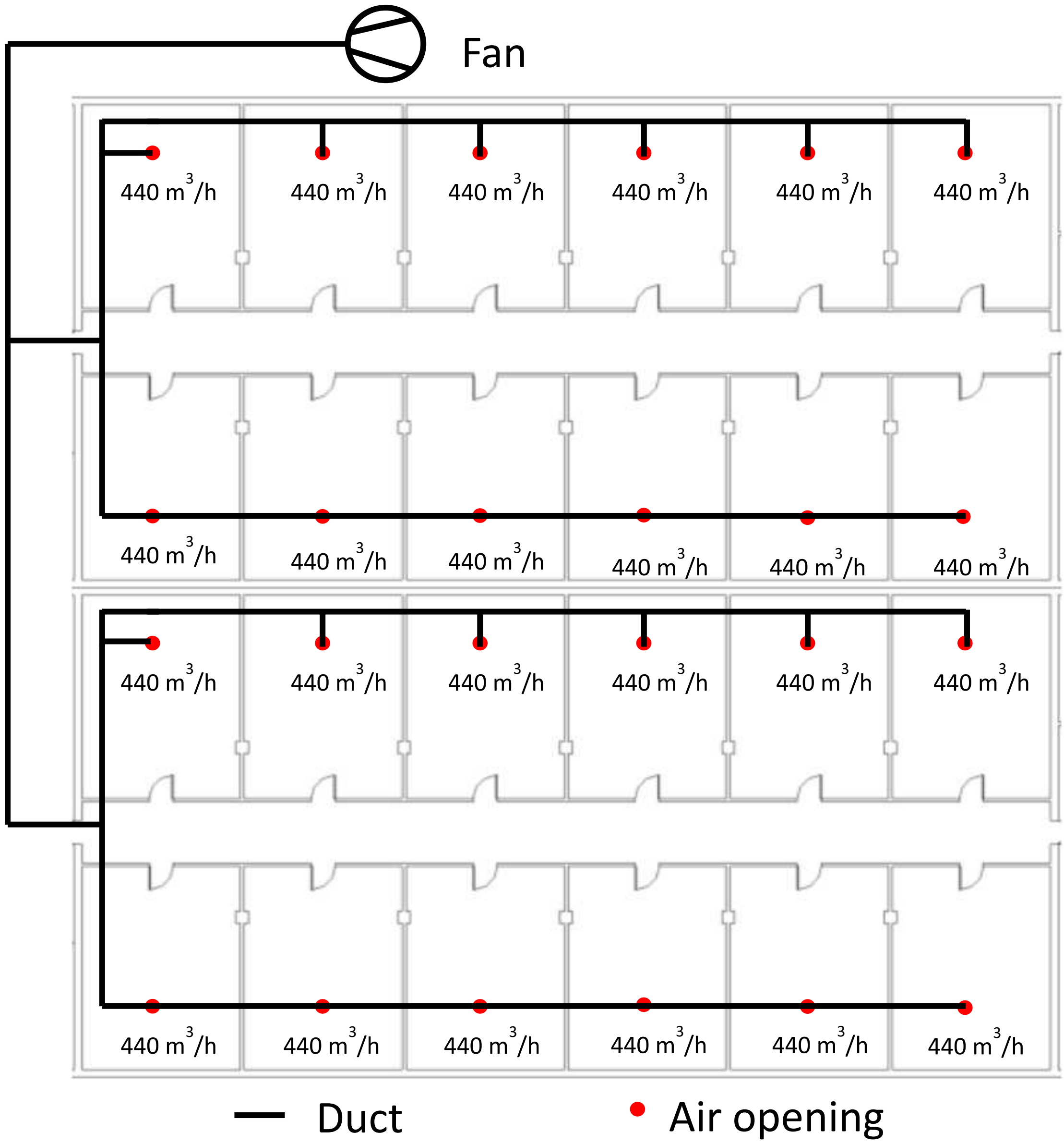

Figure 4: Existing floorplan and ductwork system for 1st and 2nd floors

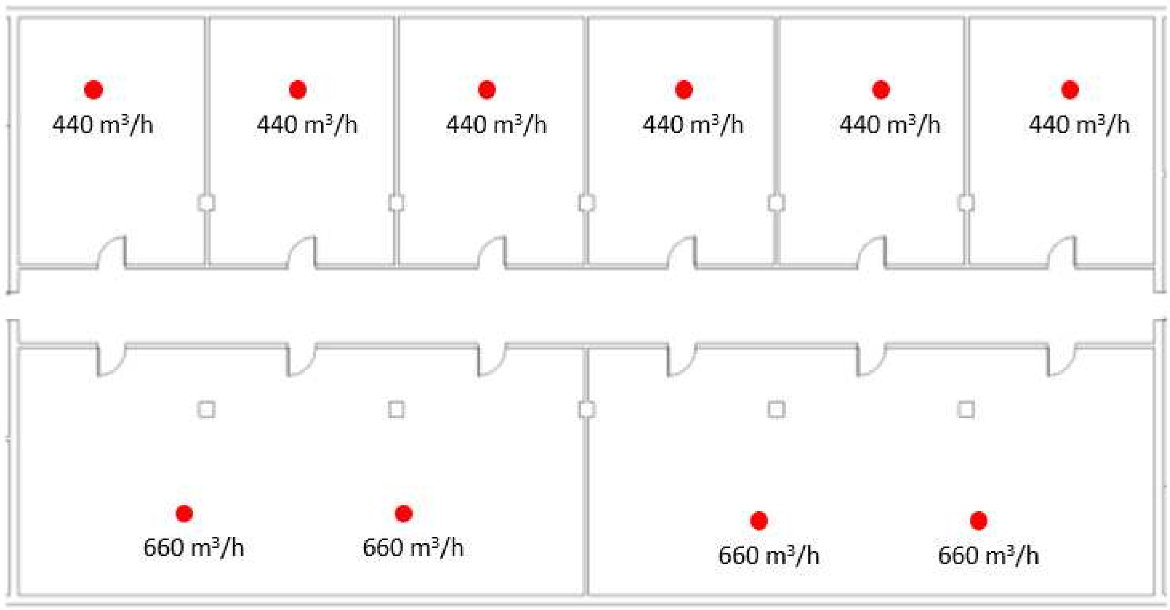

Figure 5: renovated 2nd floorplan

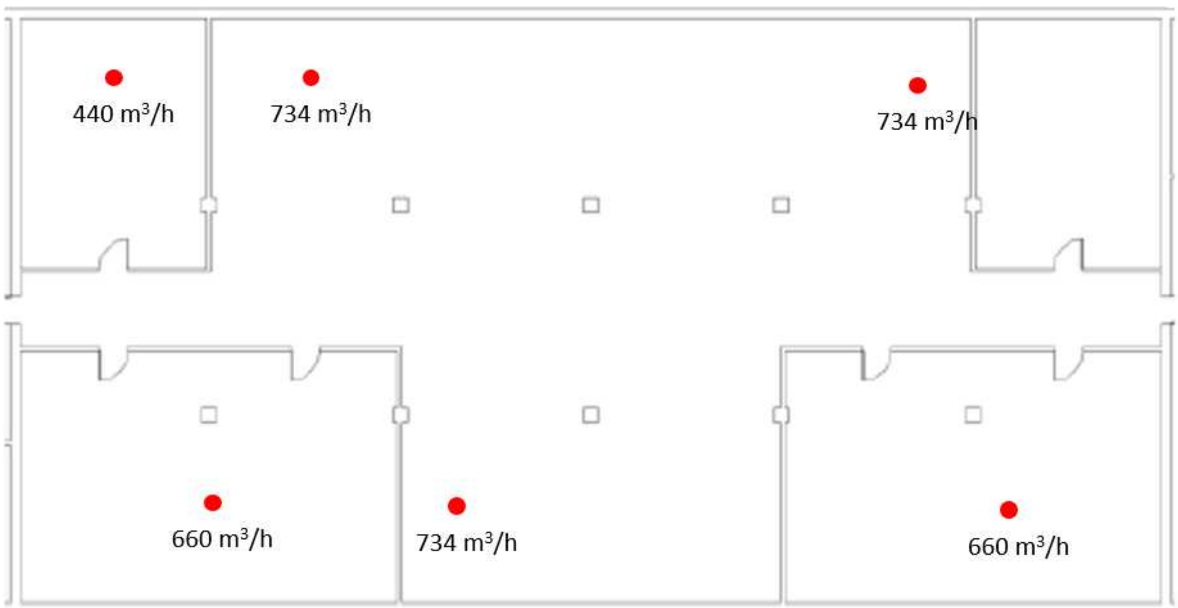

Figure 6: renovated 1st floorplan

4.2. Inputs and constraints

To ensure an unbiased assessment, we provided identical inputs to both optimization methods. For this case study, the input data described in section 3.4, namely the retrofitting floorplan, all potential ducts for the retrofitted system, and the positioning of air openings with their corresponding design airflow rates, are presented in Figure 5, Figure 6, and Figure 7. The node numbering, the heights and the velocity constraints, and the demand load (i.e., airflows) profiles are shown in Appendix B. The existing ductwork system and sizes are presented in Appendix A.

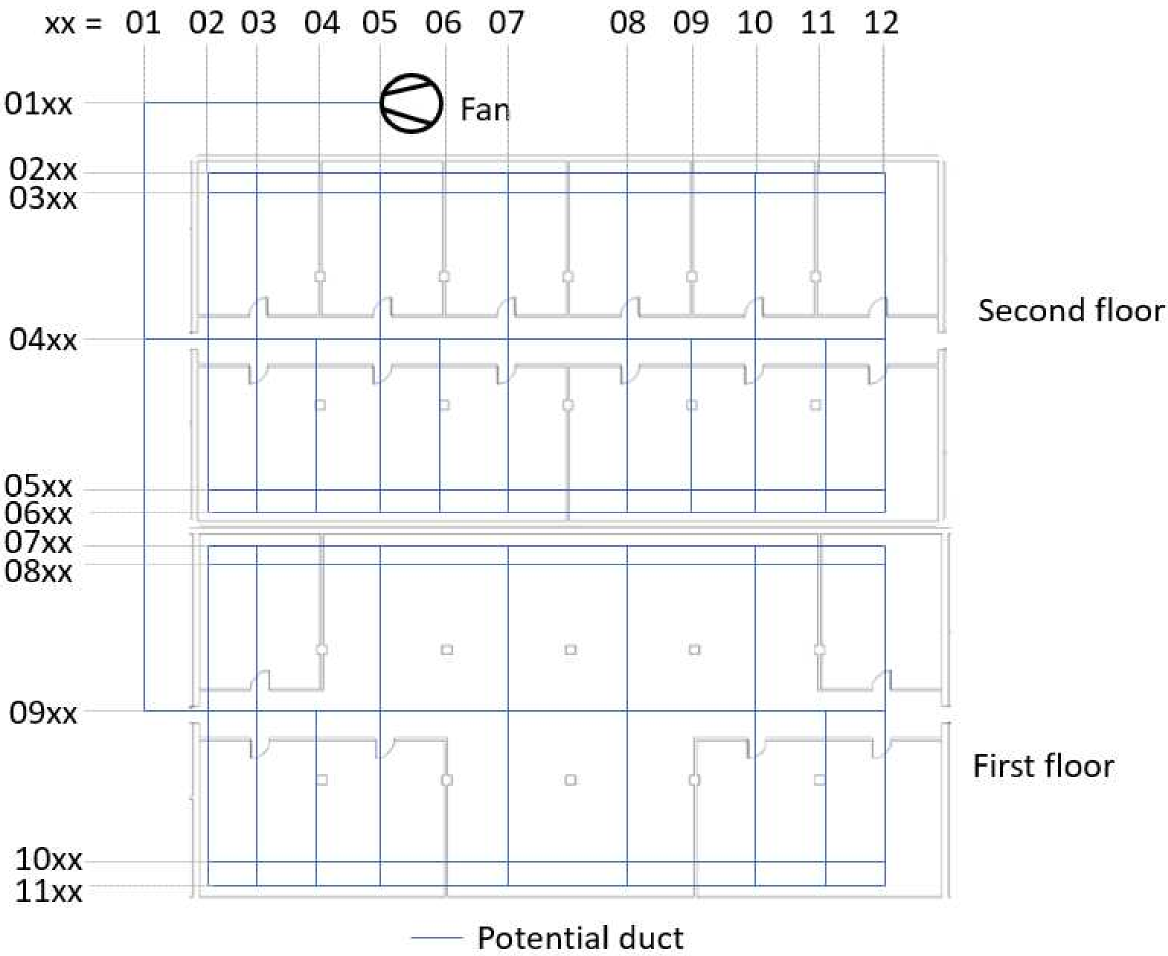

Figure 7: Input graph for retrofitting system

In addition to the above inputs, the air density (ρ) and viscosity (μ) were assumed to be 1.2 kg/m^3 and 1.562x10^{-5} m, respectively. Besides, ductwork materials used are galvanized steel with a duct roughness of (ϵ)1.5 x 10^{-3}. The existing system does not have any damaged ducts. Thus, all the existing ducts may be reused. The costs of the reused ducts are also assumed to be negligible. The annual interest is equal to the escalation rate. Therefore, by referring to Equation 3, the PWEF is equal to the amortization period, which is also equal to the life cycle of the retrofitted system (i.e., 20 years). The fan motor and shaft efficiencies were assumed to be 80% and 75%, respectively. According to the Belgian electricity grid mix, the present energy cost was averaged to 0.4 €/KWh.

4.3. Results and discussion

This section presents the generation of ductwork design configurations for the case study. Figure 8 illustrates the system redesigned completely after fully dismantling the existing system. Figure 9 illustrates the design configuration generated through our proposed retrofitting methodology, which promotes re-using the existing system whenever possible. It also highlights the reused duct section from the existing configurations.

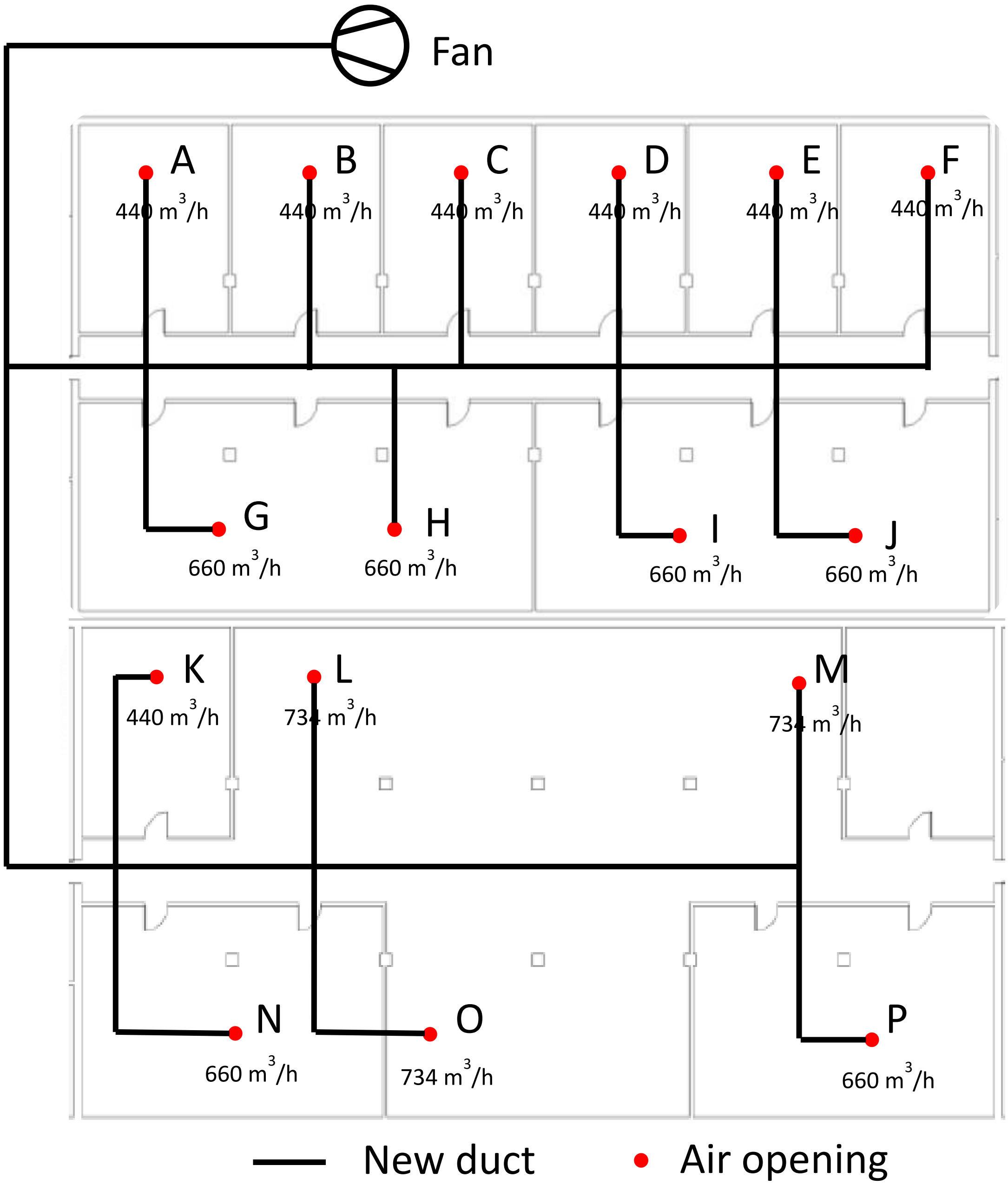

Figure 8: Completely renovated system using the design method in [10].

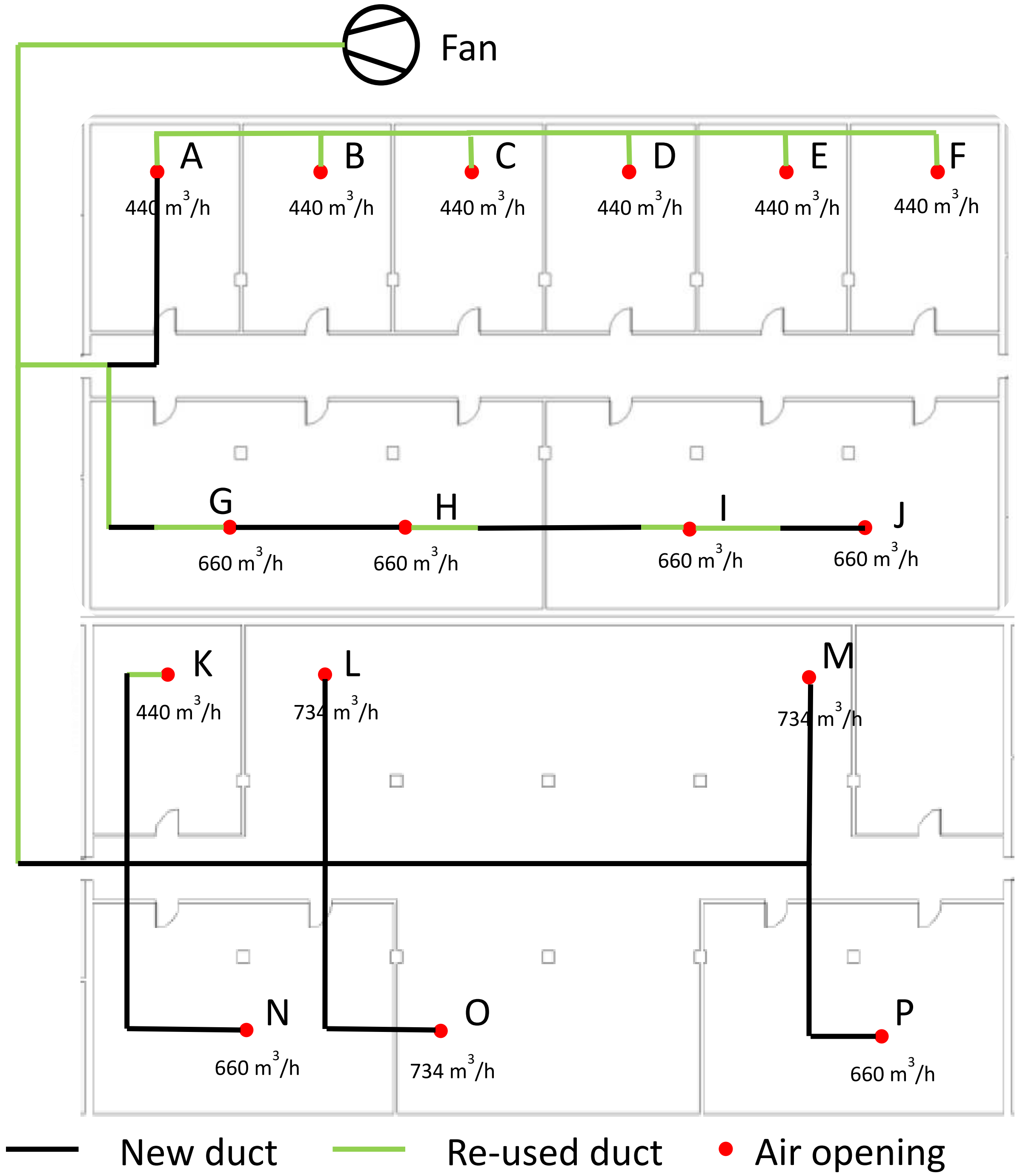

Figure 9: Retrofitted system using the developed method

4.3.1. Cost outcomes

Table 2, presents the cost outcomes for the designed ductwork configurations. These results reveal significant cost differences between the two configurations. The completely redesigned configuration has a ductwork material cost of €5,837, with a fan energy cost of €8,260, resulting in a total cost of €14,097. In contrast, the configuration developed using our proposed method has a ductwork material cost of €2,801, and a fan energy cost of €8,873, resulting in a total cost of €11,674. Comparatively, the completely redesigned configuration shows 62% lower ductwork material costs and 7% higher fan energy costs when compared to the proposed method. The increase in fan energy costs is mainly due to the cost-effectiveness of reusing existing ductwork, which can outweigh the benefits of using new, larger ductwork materials to reduce fan energy costs. This trade-off becomes evident when aiming to minimize the LCC because material and energy costs frequently conflict with each other. However, overall, the proposed method achieves a 17% reduction in total costs compared to the completely redesigned configuration.

Table 2: Optimized ductwork configurations outputs

LCC optimized new			**LCC optimized retrofitted**		
Material cost (€)	Fan energy cost (€)	**LCC (€)**	Material cost (€)	Fan energy cost (€)	**LCC (€)**
5837	8260	**14097**	2801	8873	**11674**

We acknowledge that the existing system may still hold value after dismantling, especially if the dismantled system is in good condition and can be resold. However, quantifying the cost of the dismantled system remains challenging due to various factors. These factors include the uncertainty of the market value of used components, the condition of the equipment, potential refurbishment costs (in case the system is not in good condition for reuse), and the variability in resale opportunities. Additionally, factors such as location-specific regulations, labor costs, and environmental considerations further complicate the precise estimation of the costs.

Acknowledging the complexity and numerous variables involved, we chose not to directly incorporate the cost value of the dismantled ductwork system in our presented results. However, recognizing the importance of considering the dismantled ductwork system, we aim to provide further insights in this regard. We will introduce a percentage-based factor that quantifies how much the existing system should be worth relative to its brand-new cost value.

The introduced factor acts as a threshold for decision-making. If the existing system's value is higher than this percentage of its brand-new cost, it indicates that fully dismantling the system would be materially more cost-efficient choice. Conversely, if the percentage is lower, it suggests that our proposed method of reusing the existing system is materially more cost-effective option. This approach simplifies decision-making by indicating when to opt for system replacement or reuse based on the material cost-effectiveness.

The threshold factor is expressed as follows:

$$Threshold\ \% = \frac{LCC_i - LCC_j}{X(1-a)} \times 100$$

Equation 11

With,

- i represents the completely regenerated design
- j represents the generated design using the proposed retrofitting method
- X is the brand-new material ductwork cost of the existing system
- a is the percentage of the dismantled system for the design configuration developed using the proposed retrofitting method

For this case study, the threshold percentage was 77%. This indicates that when the value of the existing dismantled system surpasses 77% of its original brand-new cost, it may prompt consideration for full dismantling and redesigning the system rather than maximizing the reuse of the existing system (i.e., using the proposed method).

Reaching a threshold of 77% or higher for fully dismantling an existing system can be challenging due to several factors. Firstly, the existing system inevitably depreciates over its usage time, causing a decline in its value. Therefore, the cost of the components in the old system would be inevitably lower compared to new components. Secondly, the process of dismantling the existing system can carry the risk of damaging components, and not all parts can be reused or resold.

In addition to the challenge of reaching the 77% threshold, it is crucial to note that fully dismantling the system can result in higher labor costs compared to partially dismantling the system as promoted when maximizing the reuse of the existing system using our developed retrofitting method. Fully dismantling the system requires removing a greater number of components, which requires more labor time and effort, thus resulting in higher labor costs compared to dismantling part of the system.

Thereby, our proposed retrofitting method, which prioritizes system reuse, is likely to be a more cost-effective alternative to full system dismantling, particularly when considering labor costs and the challenge of reaching the 77% cost value threshold for retaining the existing system.

4.3.2. Balancing outcomes

The balancing constraint is considered in both the proposed retrofitting method (see section 3.4), and the design method for new systems (completely redesigned system after fully dismantling it). Table 3 presents the *Total pressure drops* and the *Balancing %* for every path at their design flow rates for both design configurations resulting from both methods. The *Mean balancing %*, which indicates the system's balance, demonstrates high value for both designed configurations. The completely redesigned system scored a *Mean balancing % of* 83.8%, while the retrofitted optimized configuration achieved a slightly lower score at 81.9%.

Table 3: Paths balancing for the optimized configurations

	Design configuration by completely redesigning the system		**Design configuration using the proposed retrofitting method**	
Terminal Node	Total pressure drops [Pa]	Balancing %	Total pressure drops [Pa]	Balancing %
A	44.2	66.9	39.0	54.3
B	47.7	72.3	48.8	67.9
C	57.4	87.0	53.5	74.4
D	62.9	95.3	64.0	89.0
E	60.2	91.2	66.3	92.2
F	**66.0**	**100.0**	**71.9**	**100.0**
G	49.7	75.3	38.6	53.7
H	56.6	85.8	44.2	61.5
I	61.0	92.4	49.7	69.1
J	59.1	89.6	71.8	99.9
K	47.9	72.6	70.9	98.6
L	52.3	79.2	61.2	85.1
M	58.7	88.9	71.3	99.2
N	52.7	79.8	69.4	96.6
O	58.9	89.3	68.1	94.8
P	60.1	91.1	66.5	92.6
	Mean balancing %	***83.8***	***Mean balancing %***	**81.9**

Despite utilizing the existing ductwork in the proposed retrofitting method, a well-balanced design was achieved. Remarkably, the reuse of these ducts did not compromise the overall balancing of the system. This result underscores the practicality and efficiency of retrofitting as a viable approach for optimizing ductwork systems. Such balancing performance promotes the proposed retrofitting approach, in the balancing context.

4.3.3. Qualitative analysis

The proposed retrofitting methodology outperforms conventional methods through a comprehensive dual assessment approach that evaluates both cost and system performance. Unlike conventional methods that rely on simplified rules of thumb, our methodology optimizes cost-efficiency while enhancing system performance by identifying reusable duct sections from the existing system and achieving a cost-efficient and well-performed design configuration.

Driven by metaheuristic optimization techniques, the proposed method offers versatility for practical applications, addressing practical design cases. Additionally, it speeds up the design process by reducing the computational demands on engineering resources, making it particularly advantageous for time-sensitive projects and extensive retrofits. This computational efficiency is achieved through the developed heuristic optimization method.

Furthermore, our simulation-based design approach not only automates and eases the retrofitting process but also enhances its economic viability by minimizing manual labor and reducing computational resource requirements, ensuring both cost-effectiveness and optimal system performance across various project scales.

4.4. Future work

In light of the absence of an existing standardized design method driven by optimization, and given that ductwork retrofitting primarily relies on rules of thumb and the expertise of design engineers, this proposed method lays the foundational framework for approaching the comprehensive challenge of ductwork design retrofitting. Consequently, while the proposed ductwork retrofitting design method demonstrates its advantages, it is essential to acknowledge its limitations in pursuit of improving it. This work also paves the way for future research work.

The proposed method exclusively focuses on duct components (i.e., ducts and fittings), disregarding the presence of other critical elements within ductwork systems, such as silencers and pressure valves. To enhance the comprehensiveness and applicability of our methodology, we recognize the importance of incorporating these additional components into the retrofitting process. Addressing their integration enables a more holistic and effective approach to ductwork system optimization.

Another area for improvement in the established ductwork retrofitting design method lies in the oversight of ductwork leakages during the design phase. These leakages are often influenced by the quality of ductwork installation, which would influence the performance of the system. The consequences of leaky ducts encompass higher energy bills, lower energy efficiency and compromised indoor air quality. Acknowledging these effects, it is important to incorporate measures to address and mitigate ductwork leakages in the design method. By doing so, we aim to provide a more robust and comprehensive method that generates optimized solutions.

Furthermore, our current retrofitting method focuses on optimizing the design of individual ductwork systems (i.e., one ductwork system at a time). However, in real-world buildings, there often coexist multiple ductwork systems, including both supply and extraction or multiple systems originating from the presence of multiple air handling units. The optimization of one system individually can limit the optimization of another due to the architectural constraints that can propagate from one system to another. Therefore, to address this limitation, in our future work, we plan to develop a refined optimization approach capable of concurrently optimizing multiple ductwork systems, considering architectural constraints arising from various sources, ensuring a more comprehensive and efficient solution for complex building scenarios.

Finally, in this research, it was assumed that the existing ductwork configuration was known and provided as input to our proposed method and case study. However, we acknowledge that in some cases, this assumption may not always be true, and the existing system may not be fully known. This is also a main reason why some conventional approaches choose to fully dismantle the existing system and redesign it again. However, for scenarios where the existing ductwork configuration is not known, further research is needed to explore methodologies for identifying and inputting the existing system into the holistic retrofitting process. Our study underscores the significance and promise of considering the existing system in retrofitting design projects. Therefore, pursuing additional research in this direction would be worth further investigation.

5. Conclusion

In conclusion, this paper proposes a basic strategy for a holistic simulation-based ductwork design retrofitting method, using metaheuristic optimization techniques (i.e., local search and constructive heuristics). It aims to assist design engineers in the time and resource-consuming retrofitting process and enable them to maximize the reuse of existing systems and achieve well-balanced designs with optimized LCC.

The proposed method was applied to a case of a two-story school building with a repurposed use. This allowed us to demonstrate its practicality in real-world scenarios and compare it with the conventional approach of fully dismantling and redesigning the existing system. The results showed a significant 17% reduction in LCC and a well-balanced design, supporting the adoption of the approach of reusing existing ductwork systems.

In the broader context, this research contributes to the HVAC industry by offering an innovative approach to ductwork retrofitting that not only saves costs and achieves well-balanced designs but also promotes sustainability through the reuse of existing systems. However, it is important to note that before fully adopting this method, further research and improvements might be necessary to achieve a more holistic approach, as discussed in Section 4.4.

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A. Existing ductwork configuration and sizes

BN is the beginning node and EN is the end node. These numbers are determined according to Figure 7

BN	EN	D [m]	W [m]	H [m]	L [m]
104	101	0.84	1	0.6	3
101	401	0.84	1	0.6	2
401	901	0.686	0.9	0.45	3.5
901	902	0.609	0.8	0.4	0.5
902	802	0.533	0.7	0.35	1.5
802	702	0.609	0.8	0.4	0.5
702	703	0.609	0.8	0.4	0.5
703	704	0.609	0.8	0.4	1.5
704	705	0.609	0.8	0.4	1.5
705	706	0.533	0.7	0.35	1.5
706	707	0.533	0.7	0.35	1.5
707	708	0.45	0	0	3
708	709	0.355	0	0	1.5
709	710	0.355	0	0	1.5
710	711	0.25	0	0	1.5
711	712	0.25	0	0	1.5
712	812	0.25	0	0	0.5
401	402	0.876	1	0.65	0.5
402	302	0.649	0.8	0.45	0.5
302	303	0.5	0	0	0.5
303	203	0.609	0.8	0.4	0.5
203	204	0.573	0.7	0.4	1.5
204	205	0.45	0	0	1.5
205	305	0.2	0	0	0.5
205	206	0.533	0.7	0.35	1.5
206	207	0.4	0	0	1.5
207	307	0.2	0	0	0.5
207	208	0.355	0	0	3
208	308	0.2	0	0	0.5
208	209	0.355	0	0	1.5
209	210	0.315	0	0	1.5
210	310	0.25	0	0	0.5
210	211	0.25	0	0	1.5
211	212	0.25	0	0	1.5
212	312	0.25	0	0	0.5
402	502	0.609	0.8	0.4	1.5
502	503	0.5	0	0	0.5
503	504	0.533	0.7	0.35	1.5
504	505	0.45	0	0	1.5
505	506	0.533	0.7	0.35	1.5

506	507	0.4	0	0	1.5
507	508	0.355	0	0	3
508	509	0.355	0	0	1.5
509	510	0.315	0	0	1.5
510	511	0.25	0	0	1.5
511	512	0.25	0	0	1.5
802	803	0.2	0	0	0.5
705	805	0.2	0	0	0.5
707	807	0.2	0	0	0.5
708	808	0.2	0	0	0.5
710	810	0.25	0	0	0.5
902	903	0.609	0.8	0.4	0.5
903	1003	0.5	0	0	1.5
1003	1004	0.533	0.7	0.35	1.5
1004	1005	0.45	0	0	1.5
1005	1006	0.533	0.7	0.35	1.5
1006	1007	0.4	0	0	1.5
1007	1008	0.355	0	0	3
1008	1009	0.355	0	0	1.5
1009	1010	0.315	0	0	1.5
1010	1011	0.25	0	0	1.5
1011	1012	0.25	0	0	1.5

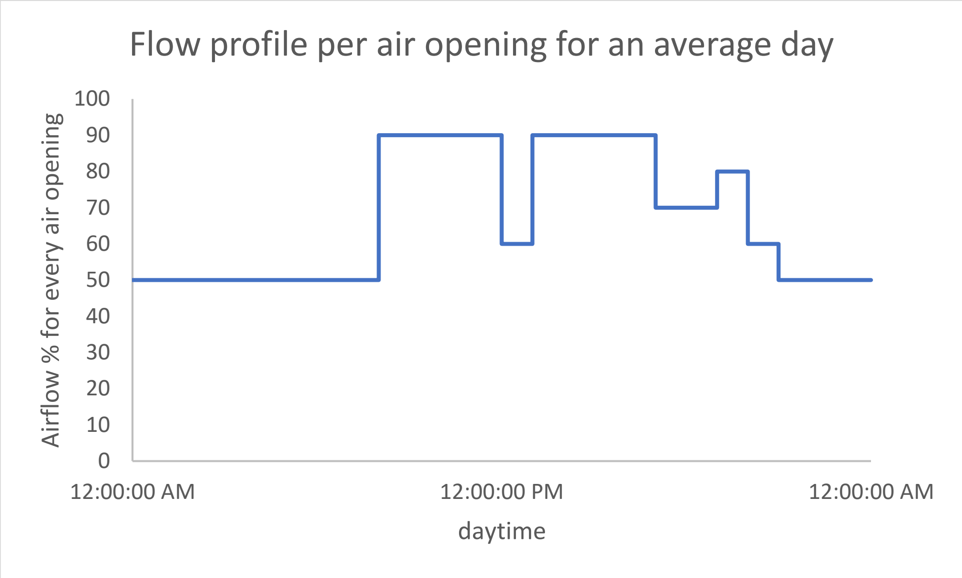
B. Ductwork retrofitting inputs

BN	EN	L [m]	Vmin [m/s]	Vmax [m/s]	H [m]
101	104	3	4	9	0.7
101	401	2	4	9	0.7
401	402	0.5	2	5	0.7
402	302	0.5	2	5	0.4
302	303	0.5	2	5	0.4
302	202	0.3	2	5	0.4
202	203	1.5	2	5	0.5
203	204	1.5	2	5	0.5
204	205	1.5	2	5	0.5
205	206	1.5	2	5	0.5
206	207	1.5	2	5	0.5
207	208	3	2	5	0.5
208	209	1.5	2	5	0.5
209	210	1.5	2	5	0.5
210	211	1.5	2	5	0.5
211	212	1.5	2	5	0.4
402	403	1.5	3	5	0.5
403	404	1.5	3	5	0.45

404	405	1.5	3	5	0.4
405	406	1.5	3	5	0.4
406	407	1.5	3	5	0.4
407	408	3	3	5	0.4
408	409	1.5	3	5	0.4
409	410	1.5	3	5	0.4
410	411	1.5	3	5	0.4
411	412	1.5	3	5	0.4
502	503	0.5	2	5	0.5
504	503	1.5	2	5	0.5
504	505	1.5	2	5	0.5
505	506	1.5	2	5	0.5
507	506	1.5	2	5	0.5
507	508	3	2	5	0.5
508	509	1.5	2	5	0.5
510	509	1.5	2	5	0.5
510	511	1.5	2	5	0.5
512	511	1.5	2	5	0.5
602	603	0.5	2	5	0.45
603	604	1.5	2	5	0.45
604	605	1.5	2	5	0.45
605	606	1.5	2	5	0.45
606	607	1.5	2	5	0.45
607	608	3	2	5	0.45
608	609	1.5	2	5	0.45
609	610	1.5	2	5	0.45
610	611	1.5	2	5	0.45
611	612	1.5	2	5	0.45
203	303	0.5	2	5	0.5
205	305	0.5	2	5	0.4
207	307	0.5	2	5	0.4
208	308	0.5	2	5	0.4
210	310	0.5	2	5	0.4
212	312	0.5	2	5	0.4
402	302	1.5	2	5	0.4
403	303	1.5	2	5	0.4
405	305	1.5	2	5	0.4
407	307	1.5	2	5	0.4
408	308	1.5	2	5	0.4
410	310	1.5	2	5	0.4
412	312	1.5	2	5	0.4
402	502	1.5	2	5	0.4
403	503	1.5	2	5	0.4
405	505	1.5	2	5	0.4
407	507	1.5	2	5	0.4
408	508	1.5	2	5	0.4

410	510	1.5	2	5	0.4
412	512	1.5	2	5	0.4
502	602	0.5	2	5	0.4
603	503	0.5	2	5	0.4
504	604	0.5	2	5	0.4
505	605	0.5	2	5	0.4
606	506	0.5	2	5	0.4
507	607	0.5	2	5	0.4
508	608	0.5	2	5	0.4
609	509	0.5	2	5	0.4
510	610	0.5	2	5	0.4
611	511	0.5	2	5	0.4
512	612	0.5	2	5	0.4
702	703	0.5	2	5	0.4
703	704	1.5	2	5	0.4
704	705	1.5	2	5	0.4
705	706	1.5	2	5	0.4
706	707	1.5	2	5	0.4
707	708	3	2	5	0.4
708	709	1.5	2	5	0.4
709	710	1.5	2	5	0.4
710	711	1.5	2	5	0.4
711	712	1.5	2	5	0.4
902	903	0.5	3	5	0.4
903	904	1.5	3	5	0.4
904	905	1.5	3	5	0.4
905	906	1.5	3	5	0.4
906	907	1.5	3	5	0.4
907	908	3	3	5	0.4
908	909	1.5	3	5	0.4
909	910	1.5	3	5	0.4
910	911	1.5	3	5	0.4
911	912	1.5	3	5	0.4
1002	1003	0.5	2	5	0.4
1003	1004	1.5	2	5	0.4
1005	1004	1.5	2	5	0.4
1005	1006	1.5	2	5	0.4
1006	1007	1.5	2	5	0.4
1007	1008	3	2	5	0.4
1008	1009	1.5	2	5	0.4
1009	1010	1.5	2	5	0.4
1010	1011	1.5	2	5	0.4
1012	1011	1.5	2	5	0.4
1102	1103	0.5	2	5	0.4
1103	1104	1.5	2	5	0.4
1104	1105	1.5	2	5	0.4

1105	1106	1.5	2	5	0.4
1106	1107	1.5	2	5	0.4
1107	1108	3	2	5	0.4
1108	1109	1.5	2	5	0.4
1109	1110	1.5	2	5	0.4
1110	1111	1.5	2	5	0.4
1111	1112	1.5	2	5	0.4
702	802	0.5	2	5	0.4
703	803	0.5	2	5	0.4
705	805	0.5	2	5	0.4
707	807	0.5	2	5	0.4
708	808	0.5	2	5	0.4
710	810	0.5	2	5	0.4
712	812	0.5	2	5	0.4
902	802	1.5	2	5	0.4
903	803	1.5	2	5	0.4
905	805	1.5	2	5	0.4
907	807	1.5	2	5	0.4
908	808	1.5	2	5	0.4
910	810	1.5	2	5	0.4
912	812	1.5	2	5	0.4
902	1002	1.5	2	5	0.4
903	1003	1.5	2	5	0.4
905	1005	1.5	2	5	0.4
907	1007	1.5	2	5	0.4
908	1008	1.5	2	5	0.4
910	1010	1.5	2	5	0.4
912	1012	1.5	2	5	0.4
1002	1102	0.5	2	5	0.4
1003	1103	0.5	2	5	0.4
1104	1004	0.5	2	5	0.4
1005	1105	0.5	2	5	0.4
1007	1107	0.5	2	5	0.4
1008	1108	0.5	2	5	0.4
1010	1110	0.5	2	5	0.4
1111	1011	0.5	2	5	0.4
1012	1112	0.5	2	5	0.4
401	901	3.5	2	5	0.5
802	803	0.5	2	5	0.4
901	902	0.5	4	9	0.5



C. LCC-optimized retrofitted ductwork configuration sizes using the proposed method

BN	EN	D [m]	W [m]	H [m]	L [m]
104	101	0.84	1	0.6	3
101	401	0.84	1	0.6	2
401	402	0.876	1	0.65	0.5
402	403	0.533	0.7	0.35	1.5
403	303	0.5	0	0	1.5
303	203	0.609	0.8	0.4	0.5
203	204	0.573	0.7	0.4	1.5
204	205	0.45	0	0	1.5
205	206	0.533	0.7	0.35	1.5
206	207	0.4	0	0	1.5
207	208	0.355	0	0	3
208	209	0.355	0	0	1.5
209	210	0.355	0	0	1.5
210	211	0.25	0	0	1.5
211	212	0.25	0	0	1.5
212	312	0.25	0	0	0.5
205	305	0.2	0	0	0.5
207	307	0.2	0	0	0.5
208	308	0.2	0	0	0.5
210	310	0.25	0	0	0.5
402	502	0.609	0.8	0.4	1.5
502	503	0.609	0.8	0.4	0.5
503	504	0.533	0.7	0.35	1.5

504	505	0.573	0.7	0.4	1.5
505	506	0.573	0.7	0.4	1.5
506	507	0.4	0	0	1.5
507	508	0.45	0	0	3
508	509	0.355	0	0	1.5
509	510	0.315	0	0	1.5
510	511	0.315	0	0	1.5
401	901	0.686	0.9	0.45	3.5
901	902	0.4	0	0	0.5
902	802	0.2	0	0	1.5
802	803	0.2	0	0	0.5
902	903	0.5	0	0	0.5
903	904	0.5	0	0	1.5
904	905	0.45	0	0	1.5
905	805	0.25	0	0	1.5
905	906	0.4	0	0	1.5
906	907	0.4	0	0	1.5
907	908	0.4	0	0	3
908	909	0.4	0	0	1.5
909	910	0.315	0	0	1.5
910	810	0.315	0	0	1.5
902	1002	0.315	0	0	1.5
1002	1003	0.25	0	0	0.5
1003	1004	0.25	0	0	1.5
905	1005	0.315	0	0	1.5
1005	1006	0.25	0	0	1.5
1006	1007	0.25	0	0	1.5
910	1010	0.315	0	0	1.5
1010	1011	0.315	0	0	1.5

D. Completely redesigned configuration after fully dismantling the existing system

BN	EN	D [m]	W [m]	H [m]	L [m]
104	101	0.876	1	0.65	3
101	401	0.876	1	0.65	2
401	901	0.686	0.9	0.45	3.5
901	902	0.533	0.7	0.35	0.5
902	903	0.573	0.7	0.4	0.5
903	904	0.573	0.7	0.4	1.5
904	905	0.5	0	0	1.5
905	906	0.4	0	0	1.5
906	907	0.4	0	0	1.5
907	908	0.4	0	0	3
908	909	0.4	0	0	1.5
909	910	0.4	0	0	1.5
910	1010	0.315	0	0	1.5
1010	1011	0.315	0	0	1.5
401	402	0.911	1	0.7	0.5
402	403	0.649	0.8	0.45	1.5
403	303	0.2	0	0	1.5
403	404	0.686	0.9	0.45	1.5
404	405	0.573	0.7	0.4	1.5
405	305	0.2	0	0	1.5
405	406	0.649	0.8	0.45	1.5
406	407	0.533	0.7	0.35	1.5
407	307	0.2	0	0	1.5
407	408	0.45	0	0	3
408	308	0.2	0	0	1.5
408	409	0.4	0	0	1.5
409	410	0.355	0	0	1.5
410	310	0.25	0	0	1.5
410	411	0.2	0	0	1.5
411	412	0.2	0	0	1.5
412	312	0.2	0	0	1.5
403	503	0.25	0	0	1.5
503	504	0.25	0	0	1.5
407	507	0.25	0	0	1.5
408	508	0.315	0	0	1.5
508	509	0.25	0	0	1.5
410	510	0.315	0	0	1.5
510	511	0.315	0	0	1.5
902	802	0.2	0	0	1.5
802	803	0.2	0	0	0.5

905	805	0.25	0	0	1.5
910	810	0.315	0	0	1.5
902	1002	0.25	0	0	1.5
1002	1003	0.25	0	0	0.5
1003	1004	0.25	0	0	1.5
905	1005	0.315	0	0	1.5
1005	1006	0.25	0	0	1.5
1006	1007	0.25	0	0	1.5

E. Circular duct prices

Galvanized steel ducts	
Diameter 80 mm	20.00 €/m
Diameter 100 mm	25.00 €/m
Diameter 125 mm	31.50 €/m
Diameter 150 mm	35.00 €/m
Diameter 160 mm	35.00 €/m
Diameter 200 mm	40.00 €/m
Diameter 250 mm	50.00 €/m
Diameter 315 mm	55.00 €/m
Diameter 355 mm	60.00 €/m
Diameter 400 mm	75.00 €/m
Diameter 450 mm	80.00 €/m
Diameter 500 mm	90.00 €/m