A BIM-Based Approach for Optimizing HVAC Design and Air Distribution System Layouts in Panelized Houses

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Abstract –

In a centralized air distribution system, the designed ductwork layout impacts the system performance and the construction time and cost. Engineers face various challenges, including spatial limitations, leading them to use assumption-based design methods to balance their design with construction requirements. As a result of this shortcoming, insufficient design details for construction and improper coordination between designers and trade workers will occur, increasing the project duration and risk for conflicts. As the construction industry shifts towards off-site and fast-paced construction methods, the design processes must comply with construction requirements to ensure a smooth transition from conventional methods to off-site construction. This research provides a scientific and systematic method for design and optimization of the HVAC air distribution system in terms of the ductwork layouts, and sizes and types of ducts to standardize the construction processes for time and cost reduction in the off-site environment. The proposed methodology utilizes Building Information Modeling for coordination of the air distribution system using a 3D database. Furthermore, a trained genetic algorithm processes the data and identifies alternative solutions. As the final step, the algorithm generates the optimal air distribution system in the BIM 3D environment for a visual assessment and detailing. The results are verified based on existing case studies in the Canadian prefabricated, panelized construction company. The potential benefits include 23% savings in duct material, whilst providing an integrated design solution with 32% less conflicts comparing to traditional design methods.

Keywords –

HVAC; Air Distribution System Layout; BIM; MEP Coordination; Constructability Analysis; off-site Construction, Optimization; Genetic Algorithm

1 Introduction

1.1 Overview

In an HVAC project, the engineer is responsible for determining the required size of the ducts and the capacity of the HVAC equipment. This design process does not consider the detailed layout of the air distribution system for construction. This leads the contractor to use past experience to determine the exact location of supply and return air terminals as well as the routing paths for the installation of floor and wall ducts. In turn, skilled trade workers are then responsible for identifying missing details in the design and resolve the conflicts based on their experience. Lack of coordination between the contractors and designers will cause conflicts during the construction, resulting in increased construction time, cost, and material waste. Uncalculated decisions and assumptions decrease building performance by creating conflicts between the building systems (e.g., plumbing) and/or structural members. This lack of information is a primary barrier to taking the leap between conventional and modular construction. Off-site construction requires extensive planning for the mechanical, electrical, and plumbing (MEP) elements to be installed on the assembly line in parallel with the construction of the panelized walls, floors, and roofs in a closed environment. The design must meet the needs of modular construction to eliminate rework and allow the construction tasks to be synchronized. The duct system must align perfectly with the structural design and other MEP elements to ensure installation is not interrupted by conflicts. If the plumbing system and ductwork overlap, the construction process of the two systems cannot take place in parallel, and there will be idle time for the trade workers.

Furthermore, the traditional experience-based HVAC design and construction do not satisfy the requirements of modular construction, which are standardized designs and sequential tasks aimed at reducing variance in the processing time of tasks on the manufacturing line. In order to address these limitations and industrialize the HVAC system in modular construction, this research integrates modular construction and design requirements when planning the air distribution system layout. This paper presents an applied approach for designing the air distribution layout, featuring an optimization algorithm that eliminates conflicts and reduces overall cost. The proposed algorithm utilizes BIM data in a tailored GA framework to determine the optimum layout for a given project. The proposed methodology was tested on various housing projects, reducing overall material waste, and eliminating design conflicts for every scenario.

1.2 Background

The MEP systems are complex and variable in terms of design and layout configurations. Improper design and integration at the planning and design stage can negatively influence the entire project. MEP construction can consist of 25%-45% of the total project cost [1]. The HVAC system is generally the most time-consuming and expensive system. One of the most challenging and time-consuming processes during the design of an HVAC system is designing the air distribution layout. The air distribution system is constructed from multi-levels of ductwork, which imposes challenges for the contractors in the decision-making process. The challenges related to the ductwork undertaken in this research are (1) determining the location of the air terminals and (2) selecting the optimum paths for connecting the duct through the floor and wall panels. The location of the air terminals and the duct paths must consider system performance and ease of constructability. During the design and planning stage, the engineer confronts parametric variations, including space occupancy and spatial constraints. The current methods for designing the ductwork focus exclusively on the size of the ducts and the fans, and the layout is not explicitly defined [2].

Space limitations and coordination between different trades are crucial factors affecting the construction time of a proposed design. The architectural design defines most of the spatial constraints and the preliminary limitations in the design and construction of an HVAC project [3]. The constraints of the air distribution system design can vary by the level of significance. They can be directly or indirectly related to system performance, e.g., occupant comfort, construction cost, and life cycle cost (LCC) [4]. Previous research suggests that because ducting system designers are forced to balance constraints and requirements with layout decisions, they often make decisions based on rules of thumb, which can come at a cost to the life cycle of the system [4].

Many HVAC design challenges are optimization problems. Researchers often focus on the most energy-efficient designs and life-cycle costs. According to [4], GA is an effective optimization technique in HVAC applications. However, in the published research projects regarding HVAC optimization, construction challenges, which include a significant portion of the cost, are not considered. The air distribution layout directly influences the construction processes and effects not only the performance of the system but the entire cost and duration of the project. The Air distribution performance index (ADPI) is a standard method for assessing how well the designed air distribution layout performs in terms of the occupant's comfort and the uniform supply of air within the building enclosure [7]. ADPI will assist the designers in the process of selecting the correct diffusers and positioning them in each space. It is a guideline for selecting supply air terminals according to the manufacturer's specifications. The application of the ADPI in the selection of commonly used diffusers for heating and low cooling modes is assessed by [9] and [10], respectively. ADPI is considered a guideline when specifying the location of diffusers prior to construction.

After the locations of the air terminals are identified, the remaining challenge is determining the optimum duct layout that will connect the air terminals to complete the design of the air distribution system layout. 3D tools are proven to be effective in facilitating an integrated design for the layout of the MEP systems. BIM is an industry-standard platform that allows all the project designers, architects, construction managers, and trade workers to seamlessly monitor project progress and exchange information in a 7-D database. BIM integrated design is an effective approach supported by a significant amount of published research. [3, 5, 6]. Utilizing a 3D collaborative database, the designers can compare their plans with the plans of other trades in order to check for interferences and to solve conflicts prior to construction. According to [5], time and cost savings are amongst the multiple benefits of BIM-based coordination as compared to conventional construction methods.

2 Methodology

2.1 Problem Structure

The objective of optimizing an air distribution layout is to generate alternative design solutions to assist the designer in achieving the most efficient performance and cost-effective results. The focus of the proposed framework is on the location of the air terminals and the designed ductwork layout required to create the HVAC system network. There are several requirements to be satisfied to create a high-performance and cost-efficient air distribution system design. (1) The location of the supply and return air terminals must follow ASHRAE guidelines [8]. (2) The duct layout must be easy to install in accordance with the building structure and other plumbing and electrical system configurations. (3) The duct layout must consist of efficient use of duct material to reduce material waste and construction time.

The scope of this research is to propose a systematic approach for determining the optimal location for the installation of the air terminals and ductwork layout. This research will use BIM for analyzing project information and GA to identify the optimal solution. The final step is to validate the result in a 3D environment. The proposed methodology is illustrated in Figure 1 below.

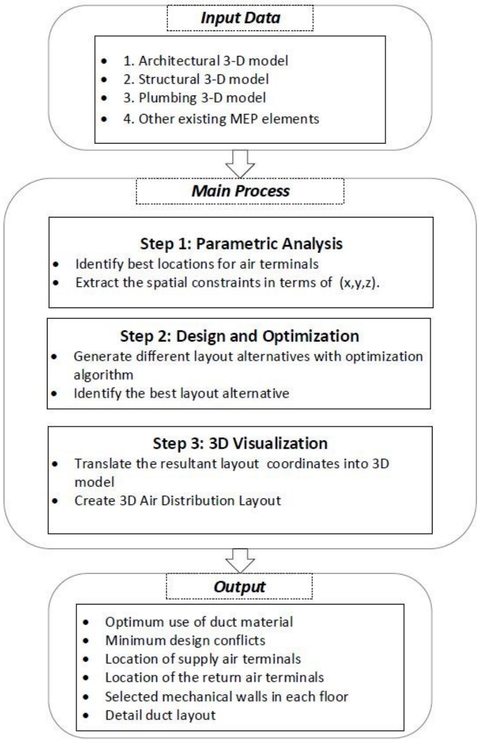


Figure 1. The proposed methodology

In order to apply the proposed methodology, manual input is required from the user, consisting of the project physical model. The 3D architectural model, 3D structural model, other existing MEP elements and a material database must be created in the BIM environment before the implementation of this methodology. The three-step processing modules are created to address the challenges in regards with the design and construction of an air distribution system layout.

The first step in the main process is the parametric analysis. In this module, the architectural boundaries required for the design of the air distribution layout are identified and extracted from the BIM model. Other physical constraints are the location of structural members and MEP elements that co-exist along with the ductwork, which may interfere with the chosen path for the ducts. The spatial constraints from BIM will be used to calculate the suitable locations for installing the supply air terminals based on the ADPI calculations and the relative location for the return air terminals based on ventilation requirements. From the parametric computation module, the extracted parameters are fed into the design and optimization algorithm. This process will assign a single position for each air terminal and asses the routes that are suitable for connecting the air terminals and creating the ductwork layout. The optimization algorithm will then generate different solutions for the layout and verify feasibilities. The layout solution, which is identified as the optimal solution, will satisfy all conditions to the highest degree and will be the resultant design solution.

The result of the design and optimization algorithm is a set of x, y, and z coordinates. The output includes the location of the air terminals and the ductwork layout relative to the chosen floor and wall panels for installation. The final step is to transfer this information back into the BIM model. The final output will be a complete air distribution layout in the BIM environment that is correlated with the project's physical model and is cost-effective. This methodology will assist the designer with the preliminary design of the air distribution network layout. Implementing this framework will automatically generate a duct network layout for any given project with optimized system performance and construction parameters. The proposed design will allow for efficient use of duct material and minimum conflicts with the building structure and MEP systems for improving constructability.

2.2 Parametric Analysis

To factor in all the data required for designing the air distribution system layout, it is crucial to follow a detailed decision-making process throughout the design. This section describes the step-by-step process of the parametric model. Just like a human designer, the proposed algorithm is trained to make decisions at each step. This section will review the process of populating the air terminals, including the supply air outlets and return air inlets, highlighting the design parameters followed by the spatial limitation and constraints.

2.2.1 Floor Mounted Supply Registers

Floor registers with a vertical discharge of supply air are identified as the preferred method of providing heat, especially in the residential houses. For selecting the optimal position of a floor register, the floor area in each space must be considered in accordance with the physical constraints as well as the occupancy requirements. The room perimeter is the ideal location for a floor register with the jet flow direction aiming towards the length of the room. [7]. Each space varies in terms of the architectural layout as well as the occupancy usage. The proposed algorithm identifies the most suitable location for the floor register in each space through a process of elimination. In this subsection, an example of a floor layout is used to demonstrate the intelligent process of selecting possible locations for supply air floor-mounted registers.

In the initial stage, each space that requires supplied air must be identified (Step 1). In the selection process, the floor space is automatically populated with a series of points (Step 2). Each point represents a possible location for the installation of floor-mounted registers. In this process, each point is eliminated, if it does not meet the design criteria. In Step 3, the points that are adjacent to the walls are eliminated because a clearance distance of 6 inches is required for construction. A floor register should not interfere with the occupancy path. Step 4 removes the points that take away from the living space. Step 5 identifies the points in front of doors and windows and eliminates them accordingly. Step 6 removes the points adjacent to external walls, and finally, Step 7 eliminates the points in each corner, which are constrained by two walls. This process is illustrated in Figure 2 below.

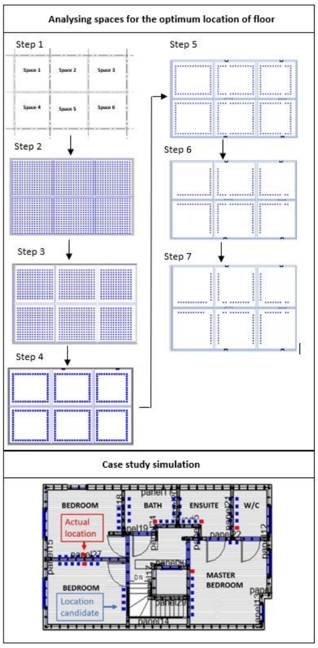


Figure 2. Identifying the best locations for installing floor mounted supply registers.

The algorithm is implemented in Dynamo and verified using the BIM simulation model created in Revit Autodesk. The blue points remaining are a set of locations suitable for the installation of the floor-mounted supply registers. The actual position where the registers are installed by the contractor exists amongst the candidate points in simulation (identified by red points). The similarity of the simulation result and the actual projects confirms the accuracy of the results. However, the final solution must only contain a single point for each space. In order to identify the optimal locations automatically, the optimization algorithm finds alternative routes for connecting the points and creating the air distribution layout. The final layout will be demonstrated in the case study section of this paper.

2.2.2 Ceiling Mounted Supply Diffusers

A ceiling-mounted diffuser is designed to diffuse the airflow in four directions instead of aiming downward. The optimum location to place a ceiling-mounted diffuser is in the middle of a room. However, each space is not perfectly symmetrical, and one side of the room boundary may be closer to the middle than the other. There are different methods for selecting the optimal location for a diffuser in each space; the position of a diffuser always depends on the room geometry, the total number of diffusers, and the required capacity. In this paper, the ADPI will be the primary design method for selecting the position of the diffusers in the designated spaces.

ADPI is a measure that indicates how well the supplied air is mixed with the existing air in the space before ventilation. It is directly related to occupant comfort, designed system performance, and energy efficiency [7]. The location for each diffuser is calculated by finding the isothermal throw distance for the selected outlet type. The throw is the farthest distance a diffuser can project the supplied air before the air stream starts losing velocity. The distance to the closest wall from the diffuser is referred to as the characteristic length. The throw to characteristic length ratio that will result in the maximum ADPI for a selected diffuser will be provided in the manufacturing guide. Table 11-1 of the ASHRAE Handbook Fundamentals Volume 1997 provides the required data for calculating the throw distance of commonly used supply air diffusers [8]. Diffuser manufacturers each have their own specifications for their products. The following equation demonstrates the calculation of the throw distance for a selected diffuser, and according to the result, the optimal position for that diffuser can be determined based on the room boundaries.

$$Maximum\ ADPI = \frac{X_{50}}{L_{Characteristic}} \qquad (1)$$

Where:

X_{50} = throw distance with 50 ft/min velocity,
$L_{characteristic}$ = room characteristic length from BIM
Maximum ADPI = from Table 11-1 [8] or manufacturers catalogue

The throw distance provides a relationship between the diffuser's performance and the room boundaries. The throw distance is used to identify suitable locations for installing the supply air diffusers by ensuring that the areal range of diffusion fits inside the space and covers at least 80% of the area. Each room has a different characteristic length, and the information obtained from BIM will allow the calculation of the diffuser's performance in accordance with the designated spaces. The following region [X_{max}-X_{min}, Y_{max}-Y_{min}] is adequate for installing the diffuser with respect to the throw distance and the room boundaries. Within this region, the characteristic length does not change. Anywhere inside the identified region, the diffuser can be installed while maintaining the areal range of diffusion inside the room boundaries. With this logic, the maximum ADPI remains the same.

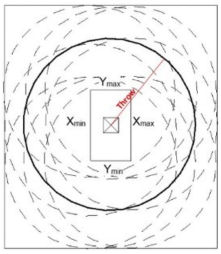


Figure 3. Identified boundary suitable for installing a diffuser

Each space has a different required flow rate, which will determine the type and the total number of diffusers required. Based on the selected diffusers and their capacities, the algorithm will determine how many diffusers need to be installed in each space. According to [7], if space requires more than one diffuser, the distance between each diffuser must be 2x the throw distance. The following figure demonstrates each diffuser's specific throw requirement in the simulation model.

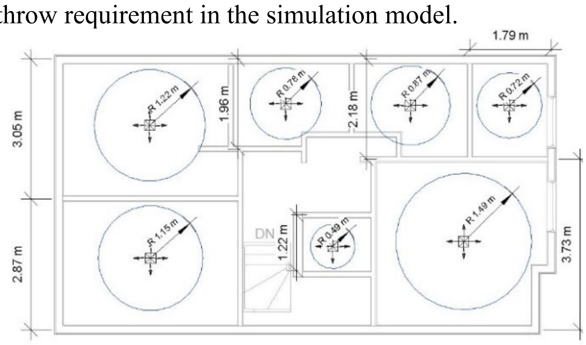


Figure 4. The range of diffusion for each diffuser

The location for each diffuser is identified, and the range of flexibility for the region of installation is determined. Each diffuser can be placed inside a box calculated based on the areal range of diffusion demonstrated in Figure 3. In order to determine the final position, the ductwork layout and accessibility for construction must be considered. The duct layout will create an air distribution network by connecting all the diffusers together. The remaining challenge is to determine the optimal layout for the system, which will be covered in the design and optimization section of this paper.

2.2.3 Return Air and Ventilation

In practice, the return air inlets are positioned as far as possible from the supply air outlets to avoid short-circuiting the conditioned air. Distancing the inlet and outlet air terminals will provide adequate time for the supplied energy to be distributed in the building before it is captured and returned to the central air handling unit. Two modes of ventilation commonly used in residential buildings are demonstrated in this research:

1. Mixing Ventilation
2. Displacement Ventilation

According to [11], mixing ventilation is suitable for heating and cooling applications. To create a network consisting of displacement ventilation, the supply air outlet, and the return air inlets must be installed in the ceilings. Displacement ventilation is a buoyancy-driven, stratified flow with high ventilation effectiveness. Based on the displacement ventilation requirements, the supply system will consist of floor-mounted registers, and the return inlets will be positioned on high walls. This design will allow the supplied air mass to gradually distribute the energy in each space as it rises toward the ceiling and exits through the vents. The figure below demonstrates displacement ventilation in a 3D model.

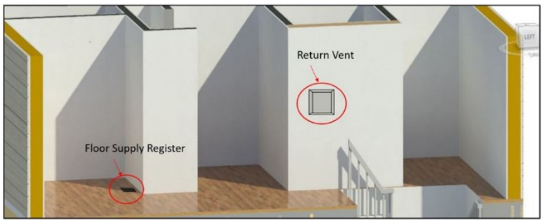


Figure 5. 3D rendering of a floor register and a side wall return vent in Revit (displacement ventilation)

Based on the mixing ventilation requirements, the supply system will consist of ceiling-mounted diffusers. The return inlets will be positioned relative to the position of the supply air outlets. The return vent must be placed in the farthest location away from all supply diffusers. The path that the supplied air travels must be far enough to allow adequate circulation and mixing of air within the space before the air stream reaches the return inlets and exits the zone.

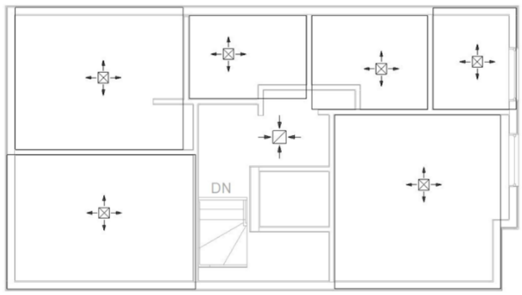


Figure 6. The position of supply and return air terminals for mixing ventilation in Revit

Depending on space flow requirements, the flow in must be equal to the flow out of each zone to provide a net-zero pressure inside the building enclosure. The supplied air must be distributed and cover the entire floor area. Therefore, the total number of supply outlets is more than the return air inlets. The building enclosure must maintain balanced pressure, and all the supplied air must eventually be ventilated. For a residential building, centralizing the return air system within the corridors of the buildings will allow the supply airflow to circulate in each room and gradually travel towards the central corridors prior to ventilation. The return air system will be designed after the supply system is set in place accordingly.

2.2.4 Spatial Constraints

Building construction is an interdisciplinary project that requires extensive planning and correspondence between all trades to ensure timely and cost-effective project delivery. Overlapping MEP elements can lead to congestion, which will increase construction time. For example, the plumbing crew will have to wait for the sheet metal crew to install the ducts and then proceed with the installation of the pipes. With the use of BIM and GA optimization, the proposed solution for the air distribution layout will comply with all spatial constraints of the project without conflicting with any other trades, ultimately reducing the cost and the total construction time.

Building structure dictates the space limitation for installing MEP elements. When the ductwork layout is interfering with structural framing, the workers need to puncture holes in the beams for routing the ducts through the framing. The rough-in work required for fitting the ducts inside the beams will increase construction time and create more construction material waste. Also, the structural integrity may be damaged in the process. Therefore, the designed air distribution system must align with the building structure. The proposed framework integrates the design parameters during the planning stage, using spatial constraints from BIM to automatically assess the number of conflicts in the alternative air distribution layout designs.

2.3 Design and Optimization

2.3.1 Problem Formulation

Once the location for all the air terminals is identified, the remaining challenge is connecting each air terminal to create the final air distribution system layout. The entire system will be constructed from two main parts.

1. Main ducts:
   - The largest duct carrying the highest flow rate from the central air handling unit to each floor
   - The horizontal segment of the main duct is centralized in each floor to reach both sides of the building
   - The vertical segment of the main duct connects each floor and exists in the mechanical walls
2. Branch ducts:
   - Smaller in cross-section
   - Deliver the flow required from the main duct to the diffusers in each space

When considering a duct network, the appropriate route for the main duct carrying the highest flow rate must be considered first. The main duct is often placed along the building corridors or the centreline of the building to have almost equal distance from the furthest air terminals in both directions; this creates a more balanced system in terms of pressure drops due to the friction losses in the duct channel. The branch ducts can be constructed partially from flexible duct material. The branch ducts are required to carry the supply air from the main duct to the location of each air terminal.

The length of the designed system is calculated using a set of coordinates extracted from the project model. These points will be categorized into two groups: endpoints — the location of the air terminals, and the starting points —the connection with the main duct. The distance between the two points will be equal to the length of that duct section. The total length is calculated by the sum of all the branch ducts plus the length of the main duct.

2.3.2 Genetic Algorithm Optimization (GA)

i. Multi-objective Optimization:

The application of GA is used in modern construction problems with multi-objective targets to achieve optimal results that satisfy each parameter requirement. The random generation and nature of this algorithm create a flexible approach to a problem with multiple interacting variables. Each generation will be assessed using a defined fitness function to evaluate the level of satisfaction for each parameter based on a weighted distribution. In this research, GA considers the following objectives:

- Reduction of total duct length
- Space air diffusion (positioning the air outlets in the most effective location in each room)
- Compliance with space availability (routing the ducts through the most accessible spaces for ease of construction and minimum interference with other building components).
- Selection of the most suitable mechanical walls to install vertical duct segments

ii. Fitness Function:

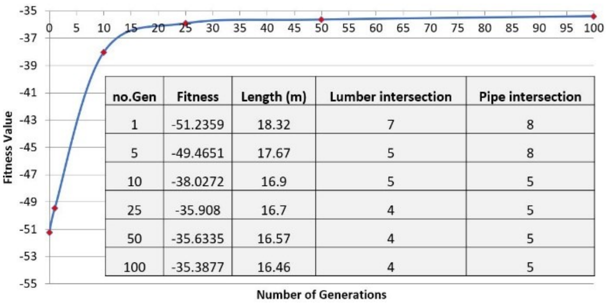
The fitness function is used to evaluate the different solutions generated by the tailored GA algorithm. The defined fitness function measures the total length of the duct system. The solution consisting of the shortest total length, is the most desirable. The two other objectives are the intersection of the ductwork with the structure and MEP elements. The fitness function evaluates the total system interferences for each solution, the system with the least intersection with the structural elements, and MEP congestion is the most favorable choice.

The fitness function is a weighted sum, which means each of the measurable objectives has a different weight on the result. The total length of the system is not as significant as the duct path intersection with the structure; therefore, more weight is assigned to the latter objective. The user can decide which objective is more important and assign the weights accordingly. Each variable is assigned a negative value because the target is reducing these parameters.

$$\text{Fitness Value} = -(W_1)\ \text{Length} + -(W_2)\ \text{MEP Congestion} + -(W_3)\ \text{Structural Interference}$$

iii. Generation vs. Improvement:

The GA starts with generating random solutions and improves the results over each generation. The graph below demonstrates the applied GA on a sample case study with a system of supply air ceiling mounted diffusers. The tabulated results display the total length of the system, the total intersection with the structural members, and the total congestion with MEP members reducing over the evolution process. The result is an air distribution layout solution that satisfies all the conditions as much as possible. Table 1 demonstrates the improvement of the solution over generations. The fitness value is the weighted sum of the total duct length, the number of intersections between the duct and the structural lumbers, and the number of overlapping with the plumbing system.



no.Gen	Fitness	Length (m)	Lumber intersection	Pipe intersection
1	-51.2359	18.32	7	8
5	-49.4651	17.67	5	8
10	-38.0272	16.9	5	5
25	-35.908	16.7	4	5
50	-35.6335	16.57	4	5
100	-35.3877	16.46	4	5

Table 1. Improvement of the fitness value over the process of evolution (Fitness Value vs Generation)

3 Case Study

This section presents a review of the real-world case study where HVAC system construction was identified to be overly time-consuming in panelized construction. The proposed methodology has been implemented, and the highlighted finding validates the given framework. A new and improved design for the air distribution system layout, providing time and cost savings by improving constructability, is proposed in this section. This approach was implemented on four multi-level houses with different layouts. Off-site construction is used for manufacturing these houses. The purpose of off-site construction is to enforce fast-paced construction. During construction the installation of the duct system took a long time due to the following reasons: First, the plumbing and the ductwork were installed in the same planum spaces, which prevented the simultaneous installation of the two trades; and second, the selected ductwork layout required excessive rough-in work, which required many holes to be made in the beams for routing the ductwork.

The following example includes the 3D model of a 3-storey single-family home with an area of 1200 ft^2. Following the framework presented in this paper, the 3D BIM model will be the primary source of data for generating the air distribution system layout. Figure 7 outlines the process for implementing the proposed methodology. This process is applied to four different cases, and the consistent results validate the accuracy of the methodology. Figure 8 demonstrates the three optimization objectives that have improved in comparison with the original design used by the company. The results presented highlight the total savings in terms of the duct length, which is approximately 10 meters (23%). Five intersections with TJI Joists were eliminated, representing a 25% reduction in drill-through holes in the structure. Furthermore, the plumbing and the ductwork did not overlap, thereby eliminating conflicts. Another significant benefit is that the design and drafting time will be reduced because the process of designing the layout and modeling it in a 3D environment is done automatically by applying the proposed algorithm.

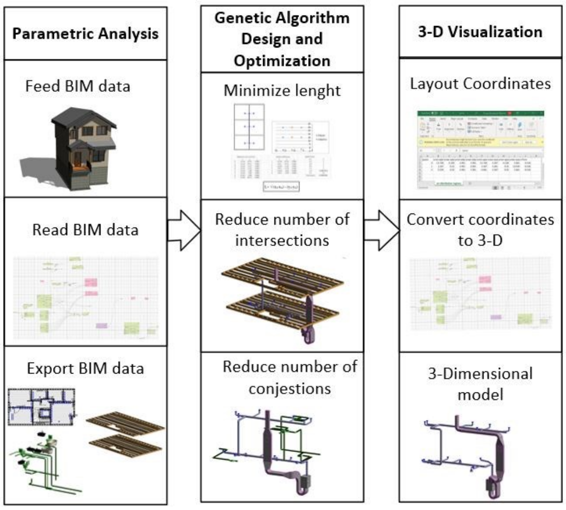


Figure 7. Framework for applying the methodology on the case study

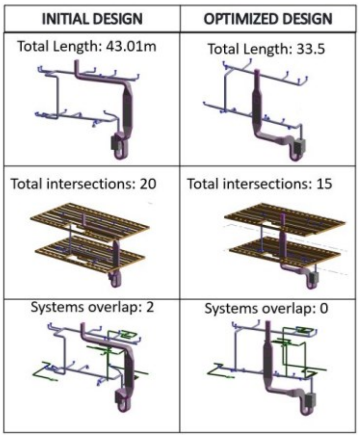


Figure 8. Benefits of the result with comparison

4 Conclusion and Future Work

HVAC systems play a significant role not only in the final performance of the project but also in the initial investment cost and the total construction duration. Assessing alternative solutions during the planning stage will allow the construction process to be applied with more certainty in the outcome, meaning fewer change orders and less waste in the time for the contractors solving conflicts and making assumptions for the missing details. Experienced contractors often produce the best results, but it is proven in this research that this knowledge can be programmed artificially with effective results. The final results include 23% savings in duct material, whilst providing an integrated design solution with 32% less conflicts comparing to traditional design methods. For future work, it is recommended that this framework be applied in compliance with Industry Foundation Classes (IFC). Energy simulation and Computational Fluid Dynamics (CFD) can also be integrated into the process to evaluate the energy efficiency of the results. This framework can be expanded for larger and industrial projects.

Acknowledgments

The author would like to acknowledge the support of ACQBUILT Inc. for providing the necessary data for implementing this research as well as sharing the challenges in the manufacturing line regarding the industrialization of the HVAC system.

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