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

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Abstract

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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 per day comparing to traditional design methods, which can potentially save about $10,119.5 and 175 man-hours per week.

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HVAC	Heating, ventilation, and air conditioning
MEP	Mechanical, electrical, and plumbing
BIM	Building information modeling
ADPI	Air distribution performance index
GA	Genetic algorithm
API	Application programming interface
3D	3 dimensional (x,y,z)
2-D	2 dimensional (x,y)
ASHREA	American society of heating, refrigeration, and air-conditioning engineers
FPM	Foot per minute
CFM	Cubic foot per minute
HRV	Heat recovery ventilation

CAD	Computer aided design
CFM	Computational fluid mechanics
AHU	Air handling unit
LOD	Level of details
IFC	Industrial foundation classes
LCC	Life cycle cost
PMV	Predicted mean vote
PPD	Predicted percentage dissatisfied

Chapter 1: Introduction

1.1 Background and Motivation

Mechanical Electrical and Plumbing (MEP) system's construction can make up 25-45% of the total project cost [7]. Improper design and coordination at the planning stage can negatively influence the entire project. The Heating, Ventilation, and Air conditioning (HVAC) system is generally the most time-consuming and expensive system in terms of design, construction, and maintenance over the life cycle of the building [4]. One of the challenging and time-consuming processes in the design of the HVAC system is designing the air distribution layout. The challenge is choosing the best routes for the installation of the ducts to connect every single air terminal and where each air terminal should be installed for optimal performance and ease of constructability. There are finite locations that each air terminal can be positioned within a room boundary, but only a limited number satisfy most constraints and meet performance requirements. The constraints that are imposed during the 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 system efficiency. Previous research suggests that because ducting system designers are forced to balance constraints and requirements with layout decisions, they often make decisions based on the rule of thumb, which can come at a cost to the life cycle of the system [6].

An HVAC Engineer oversees determining the size and capacity of the mechanical equipment and the ducts to ensure that each space is adequately heated and conditioned according to the building load requirements. When designing an HVAC system, the engineer is faced with parametric variations in terms of space occupancy and spatial constraints [9]. The architectural design defines most of the spatial constraints and defines the preliminary limitation in the design and construction of an HVAC project [5]. This design process does not consider the detailed layout of the air distribution system for construction. This leads the contractors to rely on past experience to determine the best location of supply and return air terminals as well as the routing paths for the installation of the duct inside the floor and the wall panels. In turn, skilled trade workers are then responsible for identifying missing details in the design and resolving construction 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 construction productivity by creating conflicts between the building systems (e.g., plumbing) and/or structural members and excessive use of material. This lack of information is a primary barrier to taking the leap between conventional and prefabricated construction.

Prefabricated construction processes are proven to reduce construction time, waste, and ultimately reducing costs [31]. Due to the proven benefits, the Canadian prefabricated housing market is growing and has garnered interest from the industry and academia. According to the Canadian Manufacture Housing Institute, approximately 16,020 single-family houses were manufactured in 2013, which accounts for 14% of all single-family houses built in Canada, and this number has been growing since [28]. Off-site construction requires extensive planning for the 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 designed services 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 the ductwork overlap, the construction process of the two systems cannot take place in parallel, imposing 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.

Although there are similarities, each building and project varies in terms of size and architectural layout. This makes it challenging for designers to achieve the most cost-effective and efficient designs suitable for each project. As a result, the time and cost associated with the construction of the MEP services remain significantly variable. Therefore, many companies decide to install ductless systems such as split air conditioning and electrical baseboard heaters. However, a ducted HVAC system is a preferred method for larger and multi-level buildings for optimal energy usage and occupant comfort; however, connecting the ductwork in modular panels is difficult, which encourages companies to opt for a ductless system. In order to address these limitations and industrialize the HVAC system in modular construction, this research aims to address the challenges in the modular construction assembly line and integrate the design requirements in a systematic approach for planning the air distribution system layout. This thesis proposes a methodological approach for designing the air distribution layout, featuring an optimization algorithm that eliminates conflicts and reduces overall cost. The proposed algorithm utilizes the Building Information Modeling (BIM) data in a tailored Genetic Algorithm (GA) framework to determine the optimal layout for any given project.

In modern construction projects, BIM can be used to help the decision-making process with a visual presentation of the problem in a 3D environment. The 3D model includes project data that promotes interdisciplinary collaboration between specialty contractors, engineers, and architects. Implementation of BIM will provide all necessary data to make the best-calculated decisions when planning the air distribution layout according to the visible project constraints. With the use of 3D visualization and collision detection tools, it has been proven that BIM implementation will help save time and cost by preventing interferences between mechanical, electrical, and plumbing systems and other structural elements in the project [1]. In this research, BIM will be the primary source of data for spatial analysis and coordination for the design optimization of air distribution systems.

Project data can be used to compute alternative designs to assist the designer in achieving the most efficient and effective results. Computerized optimization models follow a similar framework that the human designer would follow to approach each problem during design. However, computers are much faster, less prone to errors, and will allow a high volume of iterations that it may be impossible to complete manually. In order to develop a systematic approach for determining the optimal location for each air terminal, this research will investigate the utilization of BIM for analyzing project information and GA to identify the most optimal solution. The results are tested on different case studies in the modular construction domain to validate the proposed methodology.

Building construction is an interdisciplinary project that requires extensive planning and correspondence between all trades to ensure timely and cost-effective project delivery. With the use of BIM and GA optimization, the proposed solution for the air distribution layout will be in accordance with all project requirements, with no conflicts within the building systems and structure. The proposed solution will ultimately reduce the cost and the total construction time. This research aims to integrate design parameters during the planning stage with spatial constraints from BIM. Based on the data collected from BIM, the air distribution layout will be automatically generated. The final solution will have the least conflicts with the building structure, other MEP elements, and will, in turn, provide the shortest length to impose cost savings during the process.

1.2 Research Objectives

The objective of the proposed research is to provide a scientific approach for optimizing HVAC design and layouts in panelized houses in order to improve performance and constructability. This study is undertaken based on the following aspects which define the scope of this research:

Main objective:

i. Provide 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 offsite environment.

Sub-objectives:

i. Comprehensive study of the current challenges affecting the design and construction of the ductwork layout in off-site construction.
ii. Standardize the design processes to find the best solution suitable for panelized buildings in BIM in accordance with ASHRAE guidelines and practical industrial approach.
iii. Develop an optimization model to meet design constraints, reduce cost, and improve constructability for the air distribution system layout simultaneously
iv. Automate and streamline the process of 3D visualization with creating the ducted air distribution system, and evaluation of the result in the BIM environment.

1.3 Thesis Organization

Chapter 2 Literature review: This chapter will present the challenges regarding the construction of the MEP systems in the conventional and modular construction methods. Significant topics related to the previous work on the use of BIM for coordination of the MEP systems and various new techniques and tools available to design engineers are reviewed. In this section, the air distribution systems design criteria according to ASHRAE standard and industrial practice are identified. Furthermore, different optimization techniques for designing an efficient HVAC system are reviewed, and the tools that are used in this research are discussed.

Chapter 3 Methodology: This chapter overviews the problem structure, followed by the step-by-step implementation of the proposed methodology. The challenges in the design process are discussed, and a parametric analysis framework is presented to perform computational analysis on the BIM project models to identify alternative solutions for the air distribution system layout. Following the parametric analysis is the proposed optimization algorithm, which is developed to cope with the different constraints and multiple objectives set forth by the parametric analysis. This allows the algorithm to generate an efficient design that will reduce cost and improve constructability. The final section will review the process of transferring the resultant solution from the optimization algorithm back to the BIM environment and the procedures required for finalizing and detailing the developed design.

Chapter 4 Implementation and Results: This chapter presents a review of the real-world case studies where the construction of the HVAC system was identified to be inefficient and time-consuming in a panelized prefabrication facility. The proposed methodology is implemented, and the results are highlighted in this chapter. The findings include different benefits in terms of design and constructability, which validates the given framework. New and improved HVAC system designs for the case study projects are proposed for saving time and cost.

Chapter 5 Conclusion: In this chapter, the summary of the overall work is presented, and the final results are highlighted. The main academic and industrial contributions are discussed, and the recommendations for future work are provided.

Chapter 2: Literature Review

2.1 Overview

This chapter reviews the importance and challenges of HVAC system construction in modular construction, including fundamental aspects of design and construction procedures for an air distribution system ductwork layout. This chapter discusses residential, non-residential, and industrial applications and identifies the standard design methods to be used in this thesis. In addition, this chapter includes recent developments in the field of HVAC design and construction, including optimization and automation tools for saving costs and time.

2.2 Modular Construction and MEP prefabrication

Modular and panelized prefabrication are emerging offsite construction technologies that have garnered interest from academics and industry leaders alike. In panelized construction, prefabricated segments of walls, floors, and roofs are made in factories and delivered to the site for installation. In modular construction, a set of volumetric 3D cubic modules with interior and exterior finishes are prefabricated and delivered to the site for assembly [3]. Interest in offsite construction can be attributed to its ability to increase productivity, sustainability, and efficiency. Numerous studies have investigated the structural and architectural design and planning in offsite construction settings to elucidate optimum modular delivery. However, research on the development of a design framework for mechanical, electrical, and plumbing (MEP) elements for modular construction has received less attention, despite the influence of these elements on construction cost and efficiency. According to [62], extensive pre-planning and interdisciplinary coordination are the main challenges posed by the offsite construction of MEP systems. In light of these challenges, buildings' structural and architectural elements are prefabricated in a controlled, offsite environment, and the MEP systems that create a functional living space remain incomplete, leaving third party subcontractors to coordinate their designs. The installation of each service requires full or partial on-site construction, which is identified as a barrier toward efficient prefabricated building delivery, imposing risk of material wastage, higher project cost, and an extended schedule.

MEP systems are complex and diverse in design and configuration. Improper integration of these elements at the planning and design stages can negatively impact an entire project. Generally, the most challenging and costly building system is the HVAC system, which can take weeks to be installed and operational, even with experienced trade workers and minimize conflicts. Offsite construction requires extensive planning for MEP elements to be installed in parallel with the construction of the panelized walls, floors, and roofs in a closed environment. According to [1], the coordination of MEP design and construction in large buildings and complex industrial projects creates significant challenges and limits the potential for prefabrication and modular construction. In order to eliminate rework and synchronize construction tasks, the engineer's design must consider the manufacturing requirements of modular construction. In HVAC installation, 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, there will be idle time for the trade workers because the construction process of the two systems cannot take place in parallel.

There are several options for heating and conditioning systems, and not all require ductwork. Ductless systems include standard electric baseboard heaters, hot water board hears, split system air handling units, and mini-split heat pumps, among others. These systems provide a local source of heating and cooling for each room and can be installed in small packages. According to [2], connecting the ductwork in modular panels is difficult, which encourages companies to opt for a ductless system. However, a ducted system is a more desirable option, especially for larger homes. A ducted system creates a network that can provide heating, cooling, and ventilation for an entire building. Such a system needs to be designed in accordance with the building structure and the prefabricated wall and floor panel configurations. Therefore, the manufacturer must specify the location for all the necessary vents and ductwork.

If sufficient detail for prefabrication of MEP elements is provided, the need for as-built measurements and on-site construction is minimized. MEP designs must consider the spatial limitations of the prefabricated structural panels and modules. MEP configurations will be coordinated with all building systems with reduced risk of conflicts and congestion, allowing the pipes and duct segments to be assembled on the manufacturing line. The following Figure 1 by [1] demonstrates how traditional construction is completed by delivering individual pipe sections to the site and assembling them one-by-one, and the second picture demonstrates how MEP sections can be prefabricated and installed as a modular package.

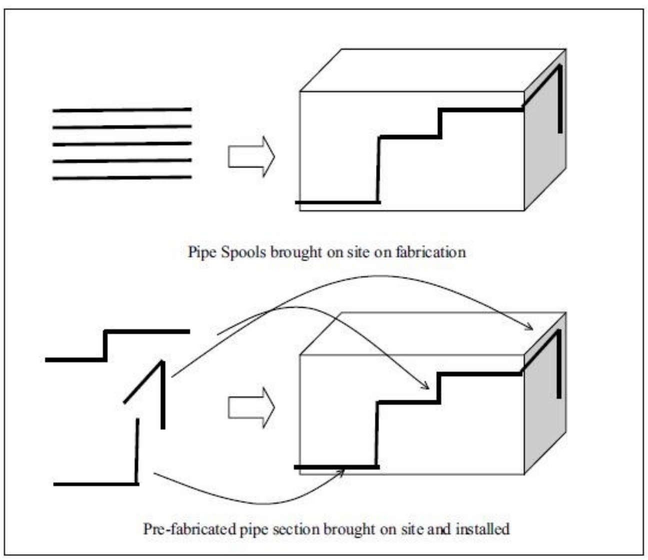


Fig. 1: Conventional site fabrication vs. prefabrication [1]

2.2.1 Lean Manufacturing Theory

Lean manufacturing was developed by the Toyota Motor Corporation to improve procedures in mass production systems by using resources more efficiently and reducing production waste [46]. The primary concept in lean manufacturing is eliminating waste by designing and producing the right quantity [47]. According to [48], waste is anything that not only contributes no value to the production system but also increases production time and cost. Waste manifests as unused material, unnecessary tasks, and idleness of resources. Offsite construction utilizes various lean manufacturing tools to create a manufacturing environment that optimizes industrial building construction by enhancing productivity and saving material [49] [50] [58]. Unlike the auto industry, building construction varies significantly in purpose, size, material, and designs. In order to achieve a controlled production line and standardized tasks, building designs must adhere to construction parameters while imposing repetitive tasks and increasing the degree of constructability in an offsite environment. The purpose of this thesis is to investigate HVAC system construction in the prefabricated building industry, with the goal of improving the production processes and eliminating waste. The picture below (Figure 2) demonstrates the waste produced on-site in relation to the flex ducts, pipes, and conduits in wood framing construction.

Fig. 2: Construction waste produced during MEP system installation

2.3 BIM and MEP Coordination

Traditionally, MEP system design and coordination are performed using 2-D graphical tools such as AutoCAD. According to [9], the engineer is responsible for providing schematic drawings, including MEP material specification and quantity; however, a detailed layout and installation instructions are not provided. The MEP coordination process traditionally takes place after the engineering design is completed. Specialty contractors, specifically those in charge of HVAC, plumbing, electricity, and fire protection system, are then responsible for the installation of these systems. Each contractor prepares a shop drawing from as-built measurements, which is then compared with the others using a light table during a coordination meeting [9]. The purposes of the coordination meeting are to identify highly congested areas, to check for clearances, and to resolve and design conflicts. A modern approach for coordinating among building systems is through BIM. This includes 3D tools such an Autodesk Revit, which are proven to be effective in facilitating an integrated design for the layout of MEP systems [5]. BIM is an industry-standard platform that allows project designers, architects, construction managers, and trade workers to seamlessly monitor project progress and exchange information in a 7-D database. The 3D physical model, the cost model, and the project schedule are defined as the first dimensions in the BIM database. The effectiveness of BIM-integrated design is supported by a significant amount of published research [1] [5] [8]. The benefits of BIM and Revit-integrated design are demonstrated in table 1 below and compared with the traditional, 2-D tool, AutoCAD [63].

Table 1. AutoCAD, Revit And BIM comparisons [63]

BIM Characteristic	Desktop CAD	Desktop Revit	BIM
Data Format of the data in the software tools	Vector and 2D Drawings	3 Dimensional parametric models	3D models plus sub systems
Workflow & Automate Tasks Steps to perform work across design and engineering roles	Manual	Semi-automated	Fully Automated
Integration Possibility to integrate multiple systems to exchange data	Minimal	Cloud, Mobile	Few Limitations
Collaboration How internal and external teams work together	Minimal	Many Possibilities	Limitless
Paper Requirements Steps and procedures are dependent on paper	Paper required for Inputs and Outputs	Both Digital with Print on Demand	Fully Digital

Using a 3D collaborative database, designers can compare their plans with those of other trades in order to check for interferences and to solve conflicts simultaneously, prior to and during the construction phase. According to [5], time and cost savings are amongst the multiple benefits of BIM-based coordination compared to conventional construction methods. When considering MEP construction projects, [8] proposes a framework for implementing the BIM development from the preliminary design phase to the construction phase in order to streamline the process and solve conflicts along the way. Implementing BIM is proven to be one of the most effective approaches for detecting and solving conflicts prior to construction. Computer-aided designs are best used for generating effective system layouts and coordinating MEP. BIM is proven to allow for accurate 3D modeling of a built environment. These models are used to detect any congestion or clashes and can evaluate the degree of constructability of the planned layout. Any issues that arise in the model can be resolved by adjustment of the parameters based on as-built measurements taken during construction in real-time. According [1], the following items are the reasons why BIM should be considered in MEP projects:

i. Limited potential for prefabrication in modular construction project
ii. Encouragement of multi-disciplinary collaboration
iii. Planning, design, shop drawings development, manufacturing, and construction process can be streamlined.
iv. More effective modular building technology
v. Tracking cost (Figure 3)
vi. Planning

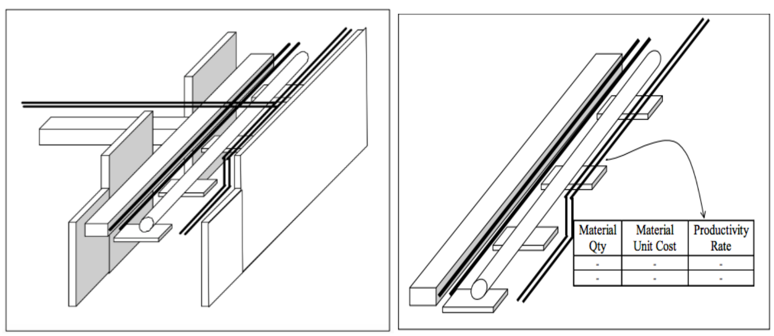


Fig. 3: BIM-based coordination as well as cost and productivity tracking of the MEP systems [1]

Numerous studies have investigated the application of BIM in solving design conflicts related to MEP systems. Interference amongst different trades is referred to as clashes, and areas with multiple trades overlapping are referred to as congested areas. The use of BIM for MEP coordination in modular construction was investigated by [62], who found that, based on two different case studies, with sufficient coordination and planning, an MEP system's rough-in can be completed in the offsite environment successfully, and only the finishes will remain to be completed on-site. However, accurately developing and maintaining a BIM model is costly, and BIM specialists are required to train subcontractors and other stakeholders to ensure smooth operation. The process of MEP development in BIM can be automated for making the design process easier; for example, a series of dynamo modules is proposed by [65] for designing the fire protection system in the BIM environment, which was proven to improve the time and accuracy of developing the design models. Furthermore, according to [66] [71], system clashes can be resolved automatically by implementing automation and machine learning algorithms in the BIM programming interface that identify design conflicts and solve the MEP system's layout.

Each class consists of a degree of tolerance. For example, if the MEP system and the structural system collide, it is considered a hard clash; in such a case, the MEP system must re-route to solve this conflict. According to [67], machine learning can be used to classify the design conflicts in BIM automatically. Furthermore, it is concluded that the current method of overlaying 2-D drawings to identify interferences of building MEP systems and structural framing is "prone to errors, causing ad-hoc rework and reduced headroom and maintainability issues" [67]. Integrating the design of the MEP systems with structural models in BIM will reduce the risk of conflict between the building structure and the MEP elements. If the ducts and pipes align with the structural beam system, they can be installed in-between the beam spacing. A long span beam system with open panels can maximize the use of ceiling space for installing MEP systems [70].

BIM is implemented from the design phase to the construction phase. [72][73] investigated the application of construction tracking and comparison of as-built vs. as-planned methods to monitor the construction of MEP systems using laser scanning and point cloud. This is a useful technique that adds to the benefits of BIM coordination capabilities because the constructed elements on-site may vary from the original design, and in order to update the changes in the project, real-time monitoring is required to prevent rework and assist in solving design discrepancies. BIM can support the life cycle performance of the projects as well. A series of dynamo models are developed by [74] to satisfy the information required for simulating different air conditioning maintenance scenarios. In conclusion, MEP systems design and construction have been revolutionized by different techniques and methods offered by the BIM collaborative techniques which assist in the design, construction, and life-cycle management of MEP systems in a building.

2.3.1 Parametric Modeling in BIM

BIM allows designers to model and register all the information that defines a building project in a graphical environment [53]. Each building element consists of parameters that define its functionality and purpose. The building design is an interdisciplinary project that includes different systems, such as the structure and the MEP systems, that interact with each other and influence design processes. The information that defines each element serves a greater purpose in the overall system by linking each element within the project to each other and, if necessary, to external databases such as national design codes like ASHRAE. BIM is a rich database that is often used for computational design. Computational design is used to solve construction and design challenges by employing modern tools such as automation, simulation, parameterization, and generative designs [51]. Computational design requires the development of algorithms that can read the project data and perform calculations using the design parameters as input to achieve the desired objective. Autodesk Revit is a leading virtual authoring tool that allows parametric modeling in BIM and helps the Architecture, Engineering, and Construction (AEC) industries to integrate their designs when developing a project [55]. Dynamo is an add-in for Autodesk Revit that acts as a language compiler for python and includes a visual programming interface, which is user friendly and makes the execution of a computational design much simpler and practical.

The application of computational design in Autodesk Revit is often used by researchers to develop and test their methodologies. BIM can facilitate energy simulation. According to [54], BIM models are useful for storing energy performance data, mainly power consumption, CO_2 emissions, temperature, occupancy, and humidity. This allows the BIM team to calculate project load intensities and provide designers with feedback before the construction begins [64]. BIM is also used for structural health monitoring, safety, and resiliency of building projects. The applications of data management for structural health monitoring in modular construction is assessed by [61]. The design parameters in Autodesk Revit can be updated automatically, which eliminates the need for other programs and software that may be used throughout a typical design process [56]. Furthermore, Revit can assist in locating design conflicts and solve construction challenges. Another important concept is generative designs that are possible with using the available parameters in the model to assess alternative design solutions automatically. Generating structural masonry walls with optimum assembly criteria is assessed by [51] for optimizing productivity and minimizing waste.

The modular and prefabrication building industry is another discipline that takes advantage of BIM-based computational designs. BIM is capable of storing construction data. In offsite construction, high productivity is achieved by combining the manual labor force with automation and machinery in the fabrication and construction processes. The applications of BIM in offsite machinery is investigated by [57] to propose a framework for evaluating machine capabilities in offsite construction. Offsite construction is growing worldwide due to the demand for sustainable construction; numerous studies discuss the application of BIM for optimizing the design and construction planning in a manufacturing setting to improve productivity, cost, and sustainability in construction [58] [61].

2.4 HVAC System Design Optimization

In an HVAC project, the engineer is responsible for determining the required size of the ducts and the capacity of the HVAC equipment. During the design and planning stages, 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 [4]. 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 preliminary limitations in the design and construction of an HVAC project [5]. Constraints of the air distribution system design can vary by the level of significance. They can be directly or indirectly related to system performance and cost, e.g., occupant comfort, construction cost, and life cycle cost (LCC) [6]. 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 [6].

Many HVAC design challenges are optimization problems [17]. According to [4], the design of the air distribution layout is done in three phases. The first phase is designing the preliminary layout; the second phase is designing the duct and fan sizes and their materials, and the last phase is selecting the damper and balancing the system pressure. Researchers often focus on the second phase by optimizing the duct sizes [6] and the control system [19] to achieve the most energy-efficient designs and life-cycle costs. The genetic algorithm (GA) has been proposed by [6] for choosing economically efficient duct sizes instead of using static pressure, equal friction, and other design methods. By using this algorithm, multiple constraints are introduced, such as the pressure balance, fan size, and capacities for discovering the optimal combinations of the duct and the number of fans required in the system. According to [6] computational fluid mechanics (CFM) analysis can be used to analyze flow behaviors inside the channels and to assign the minimum duct size and fan capacities required, which optimizes cost. GA is gaining popularity as a modern approach to solving engineering design problems involving multiple objectives, primarily the cost and time of a given project. According to [6], GA is a useful optimization technique in sustainable HVAC design applications. The fundamental structure of this algorithm allows for the selection of the best alternative combination of parameters to achieve the most favorable results [15]. This algorithm generates random, alternative virtual paths to reach a specific goal, scaling the factors in each scenario, and after iterations, pointing to the most suitable combination. Another advantage of this algorithm is that the weighted sum of the objectives is programmed to optimize; meaning, if a certain objective, for example, time, is more important to the user than another, for example, cost, they can assign a higher weight to time, and the resulting solution will be more time-efficient than cost-efficient. According to [18], GA is useful in simultaneously optimizing HVAC design and the building envelope. This is a useful concept because a building project is an interdisciplinary project, and decisions made during the design of building architecture will simultaneously influence the design of other building systems. GA codes are publicly available and easily implemented and understood with small modifications. Although GA is simple to implement, it is capable of handling complex objective functions that cannot be effectively solved by other optimization methods [18].

According to [17], HVAC problems do not require continuous and differentiable mathematical functions. Many design variables interact with each other, and the combination that satisfies the given fitness function to the highest degree is the optimal solution. Three variables and ten variable functions are investigated by [17], and it is concluded that the particle swarm optimization is effective in discontinuous objective functions, such as selecting HVAC components and pipe sizes where each decision must be selected from a discrete set. Topology optimization is another practical approach to optimize physical problems [15]. The applications of topology optimization in the design of the duct layout are investigated by [16]. According to [16], the size of the duct system can be optimized according to the fluid dynamics inside the channels. The result of volumetric topology optimization is duct sizes that may be unavailable and hard to construct. Many other optimization techniques have been studied in the field of HVAC [15] - [20], and the primary focus remains on sizing the ducts, the fans, and other HVAC components. The duct layout is not explicitly considered in any of the published journal papers. According to [4], the layout of the air distribution system can negatively affect not only its life cycle but also the installation cost. The published research regarding HVAC optimization does not consider construction challenges, which include a significant portion of the cost. The construction parameters related to the duct layout are physical problems, which are constrained by the architectural and other physical elements in the project. GA is an effective tool in optimizing parameters when designing the ductwork layout. This thesis considers the physical constraints of a building project and utilizes GA in a coding scheme to improve the constructability of the ductwork layout designs.

2.5 Space Air Diffusion

Air distribution within a designated space must maintain a rate that does not cause discomfort for the occupant. However, it must be thorough enough to mix the air in the entire volume of the space, meaning the entire room must be uniformly heated or conditioned to avoid hot spots or stagnant air. To avoid wasting the energy used for space heating and conditioning, the supplied air mass must remain in the space for an adequate time before it is ventilated. Engineers refer to the average time that the air spends in a room before leaving the space as the local mean age or the average room age [20]. In mechanical ventilation, the mean age is dependent on the distance between the supply air outlet and the return air inlets. In practice, the distance is often maximized to optimize the efficiency of the air distribution system and avoid short-circuiting of the conditioned air [21]. If comfort is the only measurement criteria, air movement will be the basis of decision making for placing the air outlet and inlets. However, it is stated by [22] that the architectural features and functional requirements of the building will ultimately determine the placement of the air terminals. This section reviews the design process for choosing the appropriate locations for the supply air outlets and return air inlets. The following section discusses the selection and placement of the air outlets for conventional, mixing, and displacement ventilation systems.

According to [10], a floor system consisting of vertical discharge of the supply air is preferred when the heating requirements are crucial. In a floor system, the supply outlets are installed along the room perimeter, with the jet flow direction aiming towards the length of the room. This system is efficient for heating and adequate for cooling when the register grilles provide the required throw. A floor supply system often consists of sill grilles and simple register grilles installed on the floor (Figure 4) with an adjustable blade to create deflection angles. Sills are often used in industrial applications to elevate the supply grills in order to prevent dust and germs from spreading from the ground with the supplied air stream. Linear slots or grill bars are also used to create a barrier in front of the windows to maintain the indoor temperature from rapidly escaping from the space. Price Engineer's HVAC handbook [21] includes details for the selection and performance of grills for supply and return air purposes.

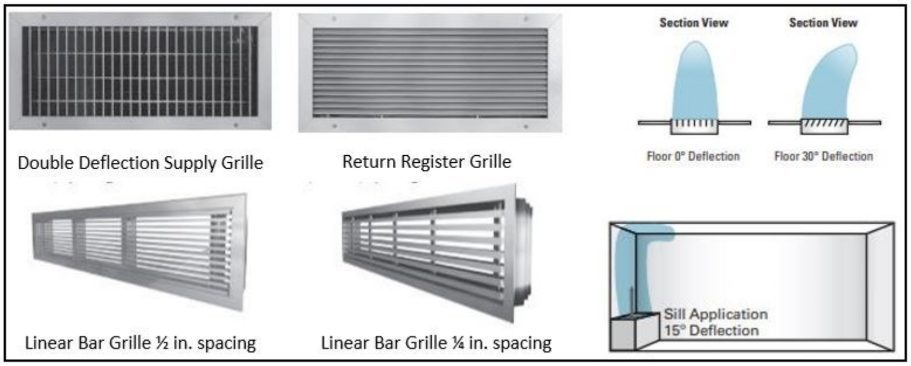


Fig. 4: Floor-mounted supply register/grilles [21]

According to [10], in a commercial setting, cooling requirements are often higher than heating requirements, and the floor area is not practical for the installation of the supply outlets. When cooling requirements are dominant, a high sidewall outlet with the direction of flow pointing to the exterior wall or a ceiling diffuser is recommended. (Figure 5) Price Engineer's HVAC handbook [21] includes details for the selection and performance of their diffusers for supply and return air purposes.

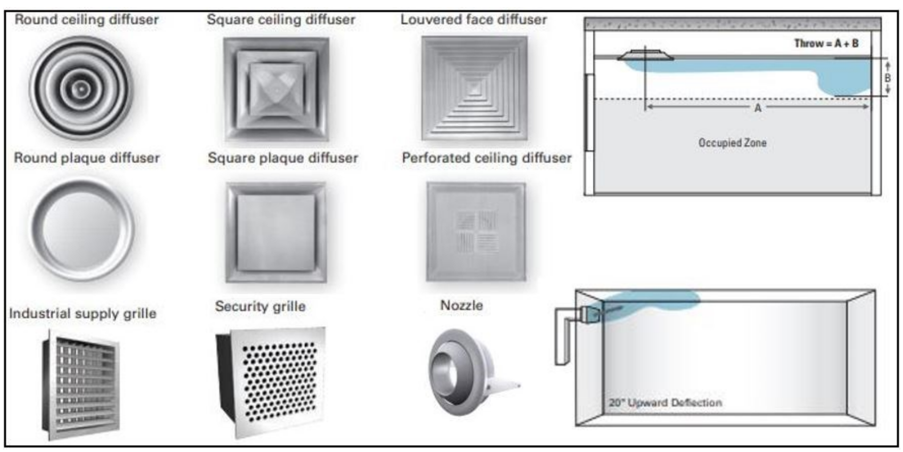


Fig. 5: Ceiling and wall-mounted supply diffusers [21]

2.5.1 Diffuser Selection and Air Distribution Performance Index (ADPI)

The air distribution performance index also referred to as the air diffusion performance index, is a common method for calculating the performance of a system. This index provides a measurement of the total air mixture within a designated space in accordance with the location of the air terminals [23]. While considering the ADPI, we can allocate the position for the air terminals to create a comfortable, sensible air movement for the occupants to prevent drought, which is the unwanted cooling of the body due to excessive air movement or an under-designed system with insufficient air mixture [10]. An effective mixture of the supplied air will allow for a uniform rate of cooling and heating in each space, which will create a more efficient system in terms of performance quality and energy usage.

Why do we use it?

ADPI is widely considered the primary method for selecting optimal diffusers to meet spatial uniformity of air velocity and occupant comfort. It is relatively simple to use and takes into account the air velocity and effective draft temperature [12]. There are other methods, such as Fanger's predicted mean vote (PMV) and predicted percentage dissatisfied (PPD), that takes into account a more in-depth assessment of occupant comfort, factoring in humidity, radiant temperatures, metabolic rate and clothing of the occupant [23]. However, at the design stage, an ADPI calculation can simply define the spacing of supply air diffusers based on the ratio of their isothermal throw and characteristic length of the room. This method is ideal for designing the preliminary layout of the air distribution system before more extensive methods for measurements are applied [12]. With access to the full geometric configuration of the building in BIM and the manufacturer's specification of available diffusers, ADPI calculation can be done for each space in the given project accordingly. BIM can support the information related to the heating and cooling loads and flow rate requirements for each room. In this thesis, the BIM model is utilized to evaluate the location and the type of diffusers suitable for each room, using ADPI evaluation as the selection guide.

How is it calculated?

ADPI is a function of the diffuser throw distance, the room characteristic length, and the effective draft temperature (EDT) [10].

i. The throw is the distance from the center of a diffuser to the farthest point, where the terminal velocity decreases to 0.25 m/s (50 ft/min). This throw value is referred to as T_{50} Imperial or $X_{0.25}$ SI. Manufacturers are required to report the throw length for each flow rate of the diffusers.

ii. The room's characteristic length ($L_{characteristic}$) is defined as the distance to the closest wall from the center of the diffuser or the perpendicular distance to the jets.

iii. The EDT is the temperature and the velocity difference between any point in an occupied space.

The basis of ADPI is identified by the percentage of measurements taken at many different locations in the occupied zone that fall within -3 °F and 2 °F effective draft temperature. The objective is to create acceptable comfort (ADPI > 80%) according to the range of T_{50}/L described in the ADPI selection guide [11]. The following equation demonstrates how the maximum ADPI is identified by the manufacturers for the selection guides [23] [10].

$$\theta = (t_x - t_c) - M(V_x - V_r) \qquad \text{Equation (1)}$$

where:

- θ – Effective draft temperature (°F or °C)
- t_x – Local airstream dry-bulb temperature (°F or °C)
- t_c – Average (set-point) room dry-bulb temperature (°F or °C)
- V_x – Local airstream centerline velocity (ft/min or m/s)
- V_r – 30 ft/m or 0.15m/s

- M – 0.07 (°F-min)/ft or 7.0 (°C-s)/m

$$ADPI = {N_\theta}/{N} \times 100\% \qquad \text{Equation (2)}$$

where:

- θ = Effective draft temperature
- N_θ – Number of points measured in the occupied space that falls within – 3 < θ < +2 °F
- N – Total number of points measured in the occupied space
- ADPI > 80%

Designing air distribution layout using ADPI

ADPI selection guides report the type of air terminal devices offered by the manufacturer and the specifications required by engineers to make design choices. Based on the space heating and cooling loads, the required capacities are predetermined by the engineers. The air terminal device's capacity and the relative T_{50}/L ratio to achieve the maximum ADPI are provided in the following selection guide. Each manufacturer is required to test their product and provide the selection guide catalog. According to each room's characteristic length, the appropriate type of device must be selected from the catalog to meet the maximum ADPI and load requirements. The following Figure 6 is an example of the ADPI selection guide table provided by ASHRAE Handbook, Fundamentals Volume, 1997.

Table 11-1 Characteristic Room Length for Several Diffusers

Diffuser Type	Characteristic Length L
High sidewall grille	Distance to wall perpendicular to jet
Circular ceiling diffuser	Distance to closet wall or intersecting air jet
Sill grille	Length of room in direction of jet flow
Ceiling slot diffuser	Distance to wall or midplane between outlets
Light troffer diffusers	Distance to midplane between outlets plus distance from ceiling to top of occupied zone
Perforated, louvered ceiling diffusers	Distance to wall or midplane between outlets

Source: Reprinted by permission from *ASHRAE Handbook, Fundamentals Volume*, 1997.

Table 11-2 Air Diffusion Performance Index (ADPI) Selection Guide

Terminal Device	Room Load, Btu/hr-ft²	x_{50}/L^a for Maximum ADPI	Maximum ADPI	For ADPI Greater Than	Range of x_{50}/L^a
High sidewall grilles	80 (252)	1.8	68	—	—
	60 (189)	1.8	72	70	1.5–2.2
	40 (126)	1.6	78	70	1.2–2.3
	20 (63)	1.5	85	80	1.0–1.9
Circular ceiling diffusers	80 (252)	0.8	76	70	0.7–1.3
	60 (189)	0.8	83	80	0.7–1.2
	40 (126)	0.8	88	80	0.5–1.5
	20 (63)	0.8	93	90	0.7–1.3
Sill grille, Straight vanes	80 (252)	1.7	61	60	1.5–1.7
	60 (189)	1.7	72	70	1.4–1.7
	40 (126)	1.3	86	80	1.2–1.8
	20 (63)	0.9	95	90	0.8–1.3
Sill grille, Spread vanes	80 (252)	0.7	94	90	0.6–1.5
	60 (189)	0.7	94	80	0.6–1.7
	40 (126)	0.7	94	—	—
	20 (63)	0.7	94	—	—
Ceiling slot diffusers (for $T_{100}/L)^a$	80 (252)	0.3	85	80	0.3–0.7
	60 (189)	0.3	88	80	0.3–0.8
	40 (126)	0.3	91	80	0.3–1.1
	20 (63)	0.3	92	80	0.3–1.5
Light troffer diffusers	60 (189)	2.5	86	80	<3.8
	40 (126)	1.0	92	90	<3.0
	20 (63)	1.0	95	90	<4.5
Perforated and louvered ceiling diffusers	11–51 (35–160)	2.0	96	90	1.4–2.7
				80	1.0–3.4

[a]For SI units, $x_{0.25}/L$ and $T_{0.5}/L$

Source: Reprinted by permission from *ASHRAE Handbook, Fundamentals Volume*, 1997.

Fig. 6: ADPI selection guide for commonly used supply air terminal devices [10]

Furthermore, the throw distance must be calculated to determine the size of diffuser suitable for the designated space. The following Figure 7 is an example of the performance data table, including the commercially available sizes for a typical round ceiling diffuser. When the engineer decides that a round ceiling diffuser is suitable, this page will be used to select the appropriate size. The following equation is used to calculate the throw distance for a selected terminal device:

$$Maximium\ ADPI = \frac{T_{50}}{L_{Characteristic}} \qquad \text{Equation (3)}$$

Where:

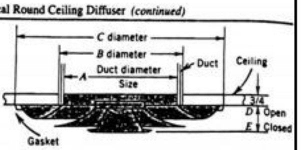
- Maximum ADPI – From ADPI selection guide
- $L_{Characteristic}$ – Distance to the closest wall in the room
- T_{50} – Throw distance with a terminal velocity of 50 ft/min

Table 11-4 Performance Data for a Typical Round Ceiling Diffuser

Size, in.	Neck Velocity, ft/min	Velocity Pressure, in. wg	Total Pressure, in. wg	Flow Rate, cfm	Radius of Diffusion,[a] ft Min.	Mid.	Max.	NC[b]
6	400	0.010	0.026	80	2	2	4	—
	500	0.016	0.041	100	2	3	5	—
	600	0.023	0.059	120	2	4	6	14
	700	0.031	0.079	140	3	4	7	19
	800	0.040	0.102	160	3	5	8	23
	900	0.051	0.130	180	4	5	9	26
	1000	0.063	0.161	200	4	6	10	30
	1200	0.090	0.230	235	5	7	11	35
8	400	0.010	0.033	140	2	4	6	—
	500	0.016	0.052	175	3	4	7	15
	600	0.023	0.075	210	4	5	9	21
	700	0.031	0.101	245	4	6	10	26
	800	0.040	0.130	280	5	7	11	31
	900	0.051	0.166	315	5	8	13	34
	1000	0.063	0.205	350	6	9	14	37
	1200	0.090	0.292	420	7	11	17	44
10	400	0.010	0.027	220	3	4	7	—
	500	0.016	0.043	270	3	5	8	11
	600	0.023	0.062	330	4	6	10	17
	700	0.031	0.084	380	5	7	11	21
	800	0.040	0.108	435	5	8	13	26
	900	0.051	0.138	490	6	9	15	30
	1000	0.063	0.170	545	7	10	16	33
	1200	0.090	0.243	655	8	12	20	39
12	400	0.010	0.026	315	3	5	8	—
	500	0.016	0.042	390	4	6	10	11
	600	0.023	0.060	470	5	7	12	17
	700	0.031	0.081	550	6	8	13	22
	800	0.040	0.105	630	6	10	15	26
	900	0.051	0.134	705	7	11	17	30
	1000	0.063	0.166	785	8	12	19	33
	1200	0.090	0.236	940	10	14	23	39
18	400	0.010	0.030	710	5	7	12	—
	500	0.016	0.048	885	6	9	15	15
	600	0.023	0.069	1060	7	11	18	21
	700	0.031	0.093	1240	9	13	21	26
	800	0.040	0.120	1420	10	15	24	30
	900	0.051	0.153	1590	11	17	27	34
	1000	0.063	0.189	1770	12	19	30	37
	1200	0.090	0.270	2120	15	22	36	43
24	400	0.010	0.024	1260	6	9	15	—
	500	0.016	0.038	1570	8	12	19	13
	600	0.023	0.054	1880	9	14	22	19
	700	0.031	0.073	2200	11	16	26	24
	800	0.040	0.094	2510	12	19	30	28
	900	0.051	0.120	2820	14	21	34	32
	1000	0.063	0.148	3140	16	23	37	35
	1200	0.090	0.211	3770	19	28	45	41

Table 11-4 Performance Data for a Typical Round Ceiling Diffuser *(continued)*

Dimensions Size *A*	*B*	*C*	*D*	*E*
6	6 1/2	11 1/8	1 3/4	1 1/8
8	8 1/2	14 3/4	2 1/8	1 1/2
10	10 1/2	18 1/4	2 7/8	2 1/8
12	12 1/2	22	3 1/8	2 3/8
24	24 1/2	43 1/4	7 3/4	6 1/8



[a]Minimum radii of diffusion are to a terminal velocity of 150 ft/min, middle to 100 ft/min, and maximum to 50 ft/min.
[b]The NC values are based on a room absorption of 18 dB referred to 10^{-13} W (8 dB referred to 10^{-12} W).
Source: Reprinted by permission of Environmental Elements Corporation, Dallas, TX.

Fig. 7: Performance data for designing typical round ceiling diffuser [10]

ADPI is not a new concept, and designers have been using this method for many years based on the ASHRAE recommendations. There have been many studies that test the accuracy of the selection guideline and improve it. The application of ADPI in the selection of commonly used diffusers for heating is assessed by [12]; it is concluded that an overhead diffuser does not perform as well under high heating modes because the buoyancy force keeps warm air on top and creates the effect of warm head, cool feet. A new ADPI selection guide is proposed by [12] for typical overhead diffusers under heating modes by utilizing the PMV index. According to [13], the ASHRAE ADPI values consider high cooling loads of 65 W/m^2–250 W/m^2, and a new selection guide is provided to meet lower cooling loads (25 W/m^2 and 50 W/m2) to prevent discomfort. Overhead diffusers are recommended by [10] for optimum air distribution under cooling mode. However, according to [25], floor air conditioning (FAC) is more energy-efficient and is in growing demand. The problem with FAC is draft discomfort because the supply air is closer to the occupants. Different locations for the FAC in a residential unit is assessed by [25], and it is recommended that the outlets be located as far from occupants as possible to reduce draft discomfort. According to [24], floor air condition can achieve the best performance with a 45° deflection angle on a 1.1m sill, with an optimum supply velocity of 2.2m/s -3 m/s. It is argued by [38] that in a perimeter grille air terminal device, the most critical factors affecting performance in terms of thermal comfort, indoor air quality (IAQ) and energy efficiency, are the supply temperatures and central flow rate. Updated 2019 tables for the calculation of ADPI under heating and cooling mode are provided in ASHRAE Research Project 1546 by [26].

2.5.1 Ventilation Requirements

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. Five different types of the ventilation system are investigated by [14], and the pros and cons of each system are identified. Mixing and displacement ventilation are the most commonly used methods. According to [14], mixing ventilation is suitable for heating and cooling applications with lower energy efficiency, and displacement ventilation is most effective for cooling applications with high efficiency and ventilation power. [33] conducted CFD simulations on both systems, and it is proven that the displacement ventilation system is superior for energy conservation and contaminant emanation in larger buildings. A method for testing the effectiveness of mechanical ventilation and natural ventilation for contaminant removal in a residential setting is demonstrated by [34], using tracer gas, along with a proposed function of contaminant removal and rate of room air replacement, to assess the air quality building problems in the design stage. The following Figure 8 demonstrates the benefits and shortcomings of different ventilation systems.

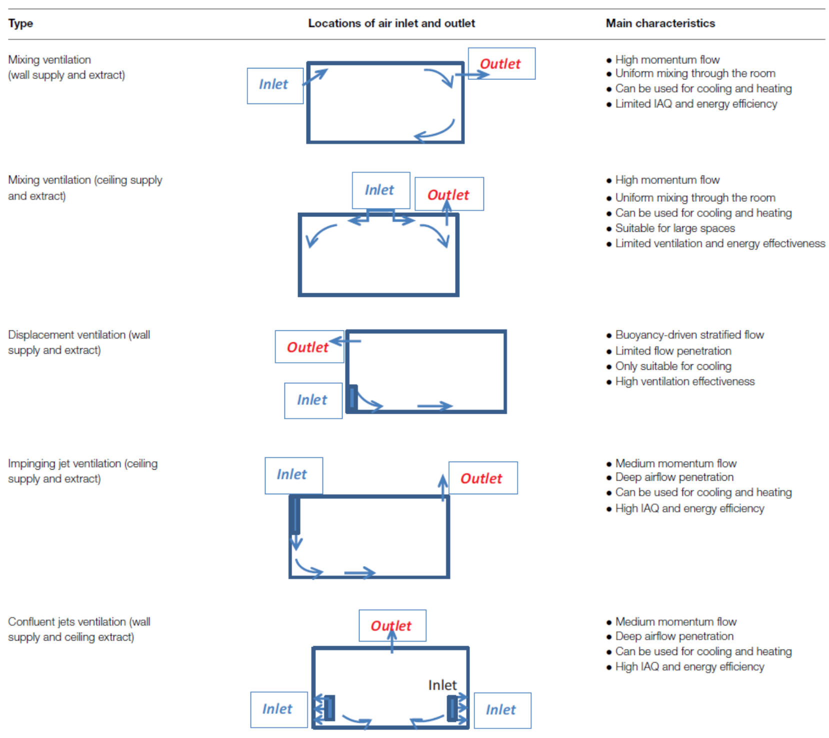


Fig. 8: Ventilation system types and characteristics [14]

Displacement ventilation is a buoyancy-driven, stratified flow with high ventilation effectiveness. Based on the displacement ventilation requirements, the supply system must consist of a supply outlet placed at a lower elevation than the return inlets. 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. Mixing ventilation is imposed by overhead supply and return air terminals.

ASHRAE's residential ventilation standard 62.2-2003 describes the ventilation requirements for residential buildings [35]. A critical review of the ASHRAE residential ventilation standard is provided by [36], who discusses the difference between the existing building and new construction requirements. Ventilation requirements for kitchen and bathroom spaces are reviewed, and a cost-effective approach for replacing the systems in existing buildings is discussed. The kitchen and bathroom often include local vents that are separate from the central HVAC system. However, to comply with health and safety, a full building ventilation analysis must consider these local vents. HVAC systems account for the largest energy use in the country [14]. Therefore, carefully planning the air distribution layout will have a significant effect on the conservation of energy within the building envelope and occupant comfort and satisfaction. Indoor air quality has a significant impact not only on occupant comfort but also on health and productivity [37]. It is concluded that in residential buildings, especially in Canada, heating is critical, particularly during the wintertime. Therefore, the floor-based outlets are more effective in terms of rapidly and uniformly heating the designated spaces. The flow of warm air mass rises as the cold, denser air tends to sink in a given space; following this principle, displacement ventilation is a commonly used system when designing the air distribution system for residential buildings. In this system, the supply air outlets are positioned at the floor level, and the return inlets are placed on sidewalls. After the supply outlets have distributed the heat in the environment, the supply air cools and lowers, gradually leaving the space through the vents.

2.6 Construction Cost and Productivity Analysis

MEP systems are complex and variable in terms of design and layout configurations. Improper design and integration at the planning and design stages can negatively influence the entire project. MEP construction can make up 25%-45% of the total project cost [7]. The HVAC system is generally the most time-consuming and expensive system in terms of design, construction, and maintenance over the life-cycle of the building [4]. Designers often come up with systems that are workable but not efficient during the construction phase. Extensive planning and coordination in the design stage will increase the degree of constructability of the system, reduce the cost of the system, and increase productivity in manufacturing and installation tasks.

There are several factors that have a direct influence on the cost and productivity of the design, fabrication, and construction of MEP systems. According to [39], interference amongst different trades, space limitations, and system complexity can cause schedule delays in MEP construction. Traditionally, the MEP systems must be delivered and assembled on the job site floor, which causes path interference and may require heavy equipment and welding in small spaces, which is impractical [39]. In industrial settings, especially in hospitals, prefabricated MEP modules are proven to be an effective method for delivering the systems [40]. Plumbing pipes, HVAC ducts, electrical trays, and the fire protection systems are packaged offsite into modules in frame boxes made from steel racks. The modules are delivered to the site for rapid installation, resulting in faster installations, safer work environments, improved quality, and reduced costs [39]. These modules are installed in the corridors of the buildings and are easily accessible for maintenance. [40] investigated the optimum design for the module configurations, as well as the optimum number of the modules that result in the most cost-effective and high productivity in the design stage. According to [41], there is a potential for saving 60% in the total project duration time in a hospital setting. Researchers are increasingly investigating this delivery method; a case study project on the Mercy hospital concluded that the overall schedule was reduced by 50% by applying modular delivery of the MEP systems [42].

One of the main factors that increase productivity in modular construction is repetition in construction tasks, which increases workers' speed in performing certain tasks. Design for manufacturing and assembly (DFMA) is a term used in the prefabrication industry that refers to a design method that considers the downstream manufacturing and construction parameters to increase the level of constructability of elements in the offsite environment, making them efficient for on-site assembly. An economic analysis conducted by [7] compares the multi-trade modular delivery of MEP versus conventional construction. The following Figure 9 demonstrates the increase in productivity of each trade and the effects of the learning curve compared to the conventional method.

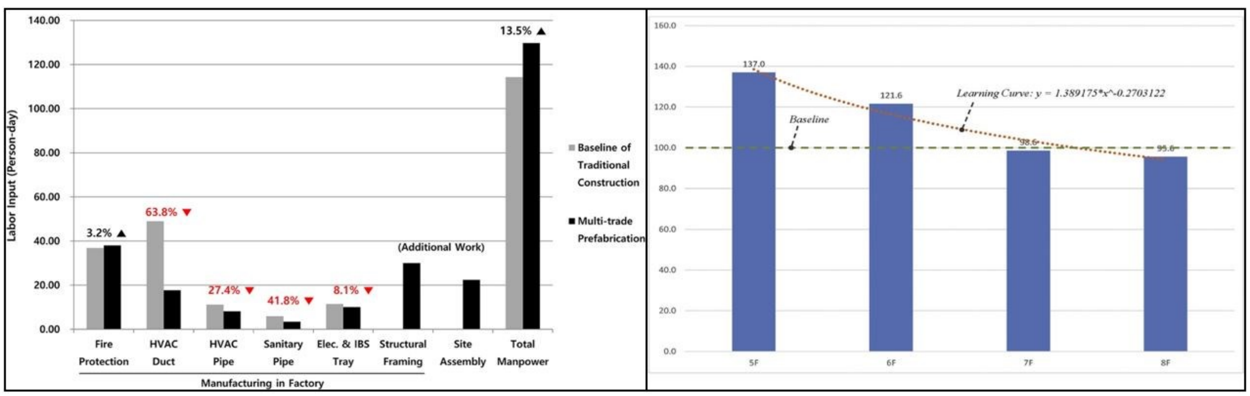


Fig. 9: Productivity and labor input in conventional construction vs. modular MEP construction [7].

Although modular delivery of multi-trade systems is beneficial in large industrial settings, the drawbacks include limited design options and training laborers to perform assembly tasks differently than they are used to. This method of delivery requires precise coordination and planning to ensure all elements fit in place when they are delivered to the project site. Therefore, modularizing the MEP system separately from the construction of the building structure can cause problems in terms of uncertainty in the difference in the design and as-built measurements, which leaves small tolerance for errors. Instead of prefabricating the MEP system separately from the structural building elements, this thesis investigates an integrated approach where the prefabricated walls and floor modules will include the MEP systems inside of them. In this manner, the risk for conflict in the offsite environment will be reduced, and more construction tasks are shifted to the offsite environment. Furthermore, panelized and modular prefabrication follows a production line that can be modeled using simulation packages such as Symphony and Cyclone for optimization of the cost and schedule in the production facility in accordance with the on-site delivery and construction schedule. An automated algorithm is proposed by [45] for real-time optimization of the schedule in a panelized production facility using Radio Frequency Identification, which produces real-time data allowing for automated adjustment and providing an advanced decision-making tool for management. Although the production process is only limited to the structural framing, with standardizing the MEP production in modular and penalized construction, the installation task and fabrication processes for the MEP components can be modeled and automated for planning and production control.

2.6.1 Ergonomics

Mechanical installation workers encounter musculoskeletal disorders at a high rate due to repetitive overhead work assembling ducts. The high-risk ergonomic tasks such as duct alignment and difficulty reaching hand tools are identified as extreme posture risks, which affect the overall productivity and health of the workers [43]. Offsite construction has the potential of reducing ergonomic risks by reducing the need for overhead construction. In offsite and modular construction, optimum ergonomics are achieved by designing an ergonomically friendly workplace environment. Optimum safety is achieved by controlling the hazards to achieve an acceptable level of risk in different workstations. A case study is conducted on the wood framing panelized prefabrication assembly line by applying an automated biomechanical simulation approach for workplace design to achieve the most ergonomic design [44]. Safety is a crucial factor in the construction industry, where an accident can lead to permanent injuries and death. By providing the laborer with a more ergonomic workplace, the productivity will increase and will result in a faster return in investment.

2.7 Literature Gaps

There is an abundance of research on the design optimization of the HVAC system for reducing energy consumption and lifecycle cost. Optimization techniques such as genetic algorithms are proven to increase the efficiency of design processes, thereby increasing system performance efficiency. Research on optimization methods often include CFD simulation and require a deep understanding of computer programming and thermodynamic knowledge. Such simulations and modeling remain expensive, time-consuming, and impractical for small to medium-sized projects, and the construction processes and initial investment costs are not considered. BIM multi-trade coordination has proven to improve the construction processes by integrating the building's multi-disciplinary designs and tracking construction conflicts. However, the published research has not explored alternative delivery methods such as offsite manufacturing in forms of panelized and modular construction in accordance with MEP construction and delivery. The proposed research will investigate recent projects as case studies to provide insight into challenges that occur when building the MEP systems in an offsite environment. This thesis proposes a more efficient design process that can be achieved with an integrated approach of design reconfiguration and automation for improved design of the HVAC system to meet the offsite construction requirements.

In order to increase efficiency, the engineer's design must adhere to the requirements of offsite construction to avoid construction conflicts and the need for reworks. For any given HVAC project, a main portion of the cost lies in the fabrication and installation of the equipment and ducts. Planning and modeling of the HVAC system in integration with the building envelope and other trades in a 3D environment with a high degree of detail is now possible with the use of BIM. Designing a high-performance system in accordance with constructability requirements can be achieved with access to the project database on the BIM platform and following standard design methods. This research will address the issue of the design and construction processes of the duct system within panelized, prefabricated wood framing buildings. To do so, we will use standard design procedures for the overhead and floor-based air distribution systems to generate optimal layout configurations suitable for offsite manufacturing, which will increase construction productivity, reduce material waste, and save costs. The proposed methodology will be used for designing the configuration and the layout of a duct network in a prefabricated building's floor and wall panels. To this end, Dynamo (version 2.1.0) is used for creating a series of modules for parametric analysis of the BIM projects created in Autodesk Revit, and then, GA will be utilized as a tool for generating designs and optimizing the layout. Furthermore, 3D visualization is used for validation and final cost and productivity analysis. Based on the literature review, the following gaps are identified:

i. Panelized construction has not been fully successful in the installation of the ducts in the offsite environment due to a lack of research in this area.

ii. Coordination of the duct system layout with other building elements is only considered after the design is completed.

iii. There is no scientific and systematic method for design and constructability analysis of the air distribution system layout in residential houses. The current systems are built based on the contractor's experience.

iv. The current HVAC optimization methods do not consider the system's layout and the construction processes and focus only on the size and selection of the equipment.

Chapter 3: Proposed Methodology

The objective of this research is to propose a systematic approach for determining the optimal locations of the air terminals and ductwork layout configuration inside the wall and floor panels. The panelized prefabrication industry can benefit a great deal from this research because the objective aims to improve the constructability of the building air distribution system in an off-site manufacturing environment. Based on the previous research, this thesis will utilize BIM for the coordination of the air distribution system and employ a GA as an optimization tool for improving the design efficiency and construction parameters. In this thesis, the scope of optimizing an air distribution layout is to generate the best design alternatives with the most efficient performance and cost-effective results. The focus of the proposed framework is on the location of the air terminals and designing the ductwork layout required to create the HVAC system network with load calculations and duct sizing, which will be completed in BIM. The proposed methodology for parameterized design optimization of the air distribution system is illustrated in Figure 10.

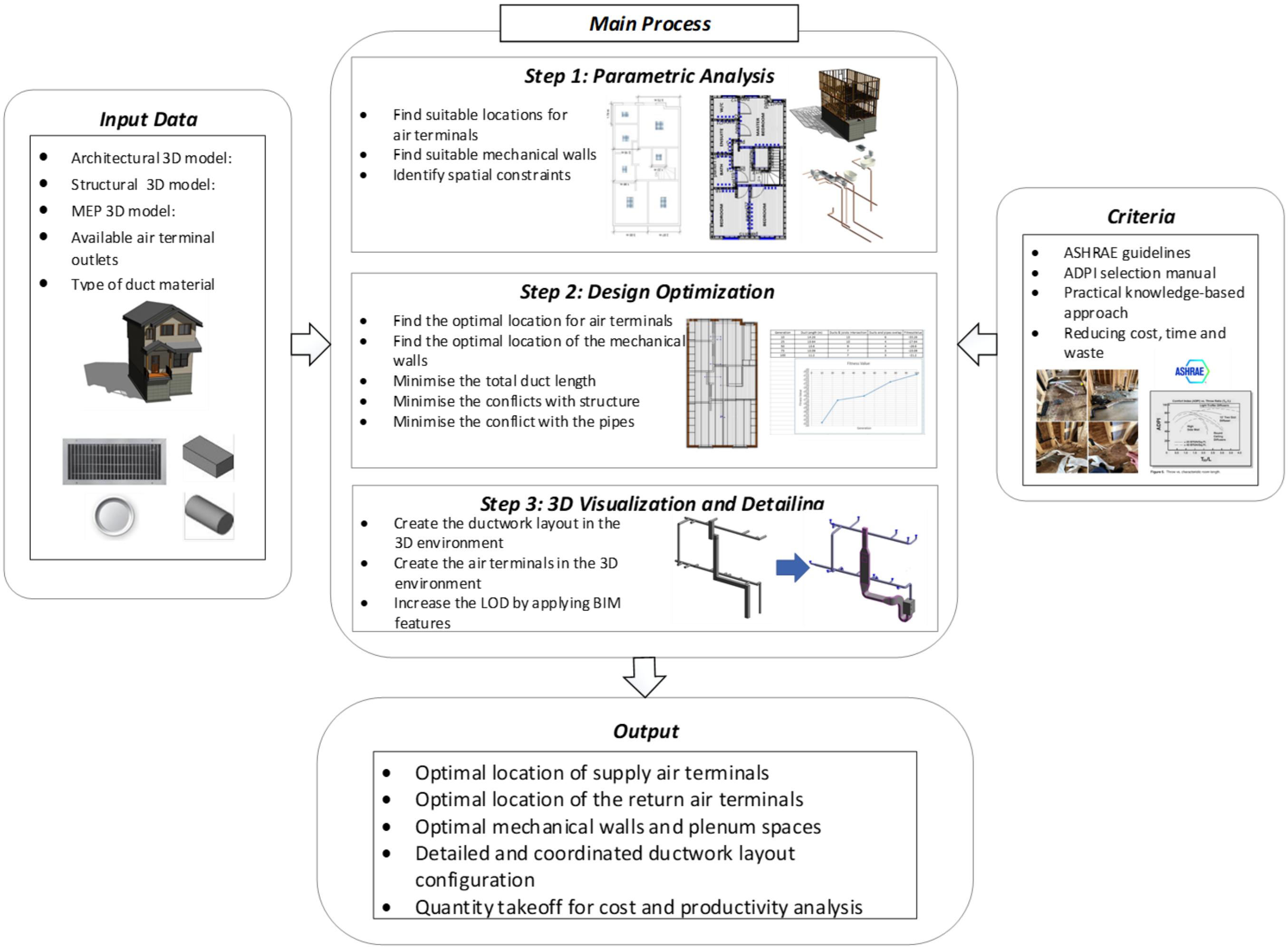


Fig. 10: The proposed methodology

The input data required for design, analysis, and optimization of the air distribution system consists of:

i. The architectural 3D model in Revit, including the floor plans and the HVAC space requirements with information on occupant's usage of each space. (e.g., bedroom, kitchen, etc.)

ii. Structural 3D model in Revit, which includes the floor and wall framing systems and prefabricated panels configurations. (e.g., beam layouts, wall framing, columns, windows, and doors.)

iii. MEP 3D model in Revit, including the plumbing system, fire protection system, and all the pipes required to be installed in the floor panels and the wall panels.
iv. Available duct materials and sizes for fabrication. (e.g., circular or rectangular ducts)
v. Type of supply and return air terminals for each floor, (e.g., floor-mounted supply registers, ceiling-mounted diffusers, sidewall ventilation grills)

There are several design criteria to be satisfied in order to develop a high-performance and cost-efficient air distribution system, including:

i. The locations of the supply and return air terminals must satisfy ASHRAE guidelines.
ii. The duct layout must be easy to install in accordance with the building structure and other plumbing and electrical systems.
iii. The duct layout must consist of efficient use of duct material to reduce material waste and construction time.

Based on the input and the criteria, the proposed methodology to design the air distribution system layout involves mainly three sequential procedures. Accordingly, this chapter is divided into three parts, which demonstrates the three steps in the main process of the proposed methodology in this research:

i. <u>Parametric analysis of the BIM model:</u> is to determine the alternative locations for the installation of the air terminals, permissible boundaries for installation of the ducts within the floor and wall panels, and identify the spatial constraints such as locations of the structural and plumbing systems.
ii. <u>Design optimization:</u> Based on the design constraints defined in the parametric analysis, a GA algorithm is used to generate the optimal air distribution system layouts, which are cost-effective construction processes.

iii. 3D visualization: is to create the air distribution system in the 3D environment based on the result of the previous optimization model and the material input defined by the user. Guidelines are provided for increasing the level of details in the final design using the purposed methodology and exiting BIM features.

The output of the proposed methodology includes:

i. The location of the supply air terminals to increase the occupant's comfort and energy efficiency of the air distribution system.
ii. Location of the return air terminals for effective ventilation and heat recovery.
iii. Ductwork layout configuration according to prefabricated floor panels and the wall panels. (horizontal and vertical duct segments)
iv. A coordinated ductwork layout that consists of minimum conflicts with the structural and plumbing systems of the building and is easier to install.
v. Efficient use of the duct material to promote cost savings and less material waste.

This methodology aims to assist the designer with the design of the air distribution network layout. Implementing this framework can automatically generate a duct network layout for any given project with optimized system performance and construction parameters. The resultant design will include efficient use of duct material and minimum conflicts with the building structure and MEP systems for improving constructability. This research aims to provide different tools and processes for increasing the accuracy of the design and elimination of time-consuming tasks during the design and construction phase of the air distribution systems in prefabricated residential buildings.

3.1 Parametric Analysis

Parametric modeling is a feature of BIM, which refers to incorporating the design parameters and the data that defines a building project in a graphical 3D model. In this research, a parametric analysis is conducted in BIM using a series of modules developed using the Revit Autodesk Application Programming Interface (API) to identify and calculate the parameters required for the design optimization of the air distribution system. Parametric analysis requires manual input from the user, consisting of the detailed BIM project model. The 3D architectural model, 3D structural model, other existing MEP elements, and a material database must be established in the BIM environment before the implementation of this methodology.

To factor in all the parameters 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 and the logic behind the parametric analysis modules developed in Dynamo. Just like a human designer, the proposed algorithm is trained to make decisions at each step. In this chapter, This thesis will be presenting the developed standard design process in populating the air terminals, including the supply air outlets and return air inlets, based on the satisfaction in both ASHRAE guidelines and practical industrial approach, especially in modular construction. Furthermore, the spatial limitation, such as the room boundaries and constraints such as the structural framing and the plumbing systems, are identified, and the formula for calculating the ductwork layout is demonstrated.

Parametric analysis is the first step in this research methodology. In this procedure, the architectural rooms layout, which defines the room boundaries required for the design of the air distribution layout, are identified and extracted from the BIM model. Furthermore, all of the physical constraints are: (i) the location of structural members; and (ii) MEP elements that co-exist along with the ductwork, which may interfere with the chosen path for the ducts. These identified spatial limitations from BIM are set as constrains for calculating suitable locations for installing the supply air terminals for each room. The location for the return air terminals is assigned based on ventilation requirements. Finally, the possible routes for the installation of the ductwork layout are coordinated with respect to the spatial constraints dictated by the existing architectural plans and MEP systems in the building 3D model for examples the room boundaries will be used to calculate the position of the outlet and inlets and the plenum space will define the acceptable routes for the duct runs. This method aims to generalize and streamline the design processes for the air distribution system layout in residential buildings. Figure 11 below demonstrates the parametric analysis framework, which is the first step in the proposed methodology. There are a series of dynamo modules developed for each type of air system, ceiling supply air, floor supply air, ceiling return air, and wall return air. The flow of information is represented in Figure 11, and each dynamo module will be described in detail in this chapter.

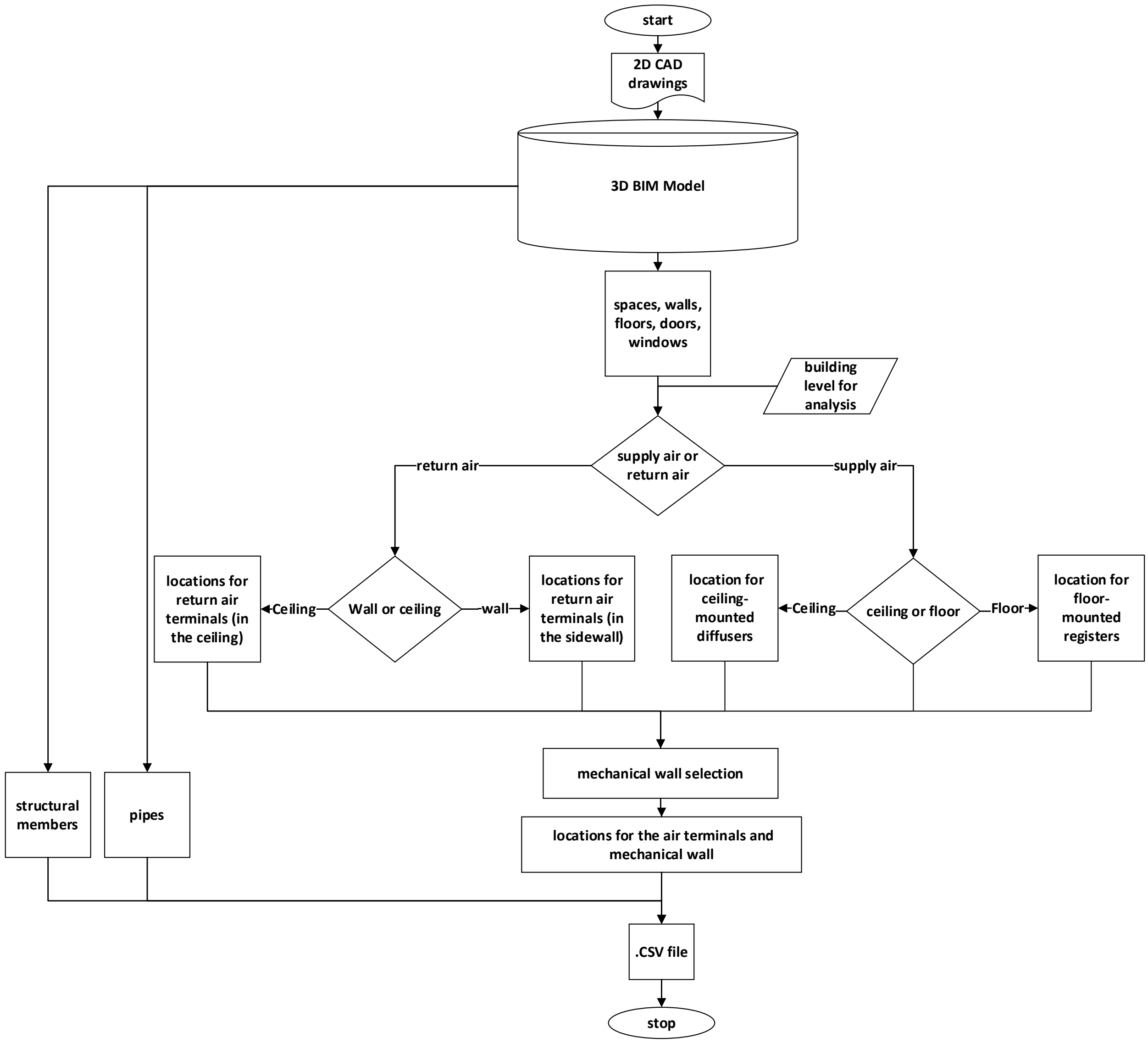


Fig. 11: Process flow of the parametric analysis

Input:

i. The architectural 3D model in Revit, including the rooms layout and the HVAC space requirements with information on occupant's usage of each space. (e.g., bedroom, kitchen, etc.) as well as the location of the doors and the windows.

ii. Structural 3D model in Revit, which includes the floor and wall framing systems and prefabricated panels configurations. (e.g., beam layouts, wall framing, columns

iii. MEP 3D model in Revit, including the plumbing system, fire protection system, and all the pipes required to be installed in the floor panels and the wall panels alongside with the ducts.

iv. The user must select the level in the building that is required for analysis because each level consists of different architectural, structural, and MEP features.

Parametric Analysis

i. A floor or a ceiling-based air distribution system must be selected in order to determine all of the suitable locations for the installation of supply air terminals. This process is referred to as **populating the air terminals**.

ii. If the floor supply system is selected, then the return system with the inlets positioned in the walls must be selected for displacement ventilation. If the ceiling supply system is set in place, the return inlets must be positioned in the ceiling for mixing ventilation. The user must select each system individually to perform the parametric analysis.

iii. The last function is determining the suitable walls for installation of the vertical duct segments referred to as mechanical walls.

iv. Alongside with the parametric analysis, the location of the structural elements, the pipes and the opening in the building are extracted in this process

Output

i. The output is a CSV file including the coordinates of all the above elements

Each step for the parametric analysis is described in more detail in this section starting with populating the air terminals.

3.1.1 Populating the Air Terminals

This section will demonstrate the knowledge-based approach to search for the optimum locations for the installation of the supply air terminal outlets and return air terminal inlets in a BIM project. A sample project is used as a Revit model to demonstrate alternative air distribution system designs. Two different systems for supply air distribution are investigated. First, the placement of floor-mounted supply registers is discussed for the application of a residential central heating system. Second, the over the head ceiling mounted supply diffusers selection, and placement process is presented in accordance with the ASHRAE recommendations and ADPI selection guidelines for optimal occupant's comfort and uniform air distribution in building enclosure. After reviewing the supply air systems, the design of the return air system for ventilation will be demonstrated. The appropriate modes of ventilation for floor and ceiling air distribution systems are presented. According to the criteria for displacement and mixing ventilation modes, the decision-making process for choosing the location of the vents (return air inlets) is demonstrated on the sample project. Based on the presented methods for positioning supply and return outlets, the populating of the air terminals is generalized and automated using the Revit API to increase the design efficiency and assist the designers in finding optimal locations for installation of each air terminal in the project.

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 (Figure 12). For selecting the optimal position of a floor register, the floor area in each room must be considered in accordance with the physical constraints such as stairs and doors as well as the occupancy requirements (e.g., bathroom, bedroom, walk-in closet etc.,). The room perimeter is the ideal location for a floor register with the jet flow direction aiming towards the length of the room [10]. Each floor layout varies in terms of the architectural layout as well as the occupancy usage. The proposed algorithm identifies the most suitable locations for the installation of the floor register for optimal performance as well as improving constructability. In this subsection, an example of a floor layout is used to demonstrate the intelligent process of selecting optimal locations for supply air floor-mounted registers. A knowledge-based heuristic algorithm framework and practical review of the decision-making process are introduced. This process is based on how the experts in the field will identify the best location for installing the floor registers according to the room geometry and architectural features. An algorithm is designed to make decisions like an experienced contractor. In each step, the proposed algorithm will eliminate the least favorable locations to create a list of suitable locations for installing floor-mounted supply registers. In this study, DesignScript was used as the programming language for analyzing and extracting the data from the BIM model, and Dynamo (version 2.1.0) is used as the language compiler for the Autodesk Revit. This section will review the logistical framework behind the developed algorithm.

Fig. 12: Typical floor-mounted registers in single-family houses in Canada

The algorithm for analyzing the Revit model was designed as a series of custom nodes in Dynamo Add-in for Revit with some input ports and output ports. Each custom node is preceded by an input such as family types, and it is programmed to compute the required data from the specified building elements. In this section, the different blocks that form the script will be reviewed with more detail, which can be useful for future development. The following Figure 13 illustrates a snapshot of the created code in Dynamo (version 2.1.0). The algorithm is designed for discovering the optimal location for the installation of the floor-mounted registers includes 13 blocks. Each block contains various nodes, and together they are designed to perform a specific task. The blocks are divided into four categories, 1-5 are BIM-based inputs; they are designed to point to a specific element in the project, such as a floor panel. These blocks are programmed to identify the configuration of the element based on the bounding box, which defines the maximum coordinates associated with the element in 3D space. Blocks 6 and 7 are user-adjustable inputs. Blocks 8 and 9 are parametric analysis blocks that perform specific calculations based on the information received from the input blocks, and blocks 10-13 are output blocks which will export the calculated results. The relationships between blocks are demonstrated below.

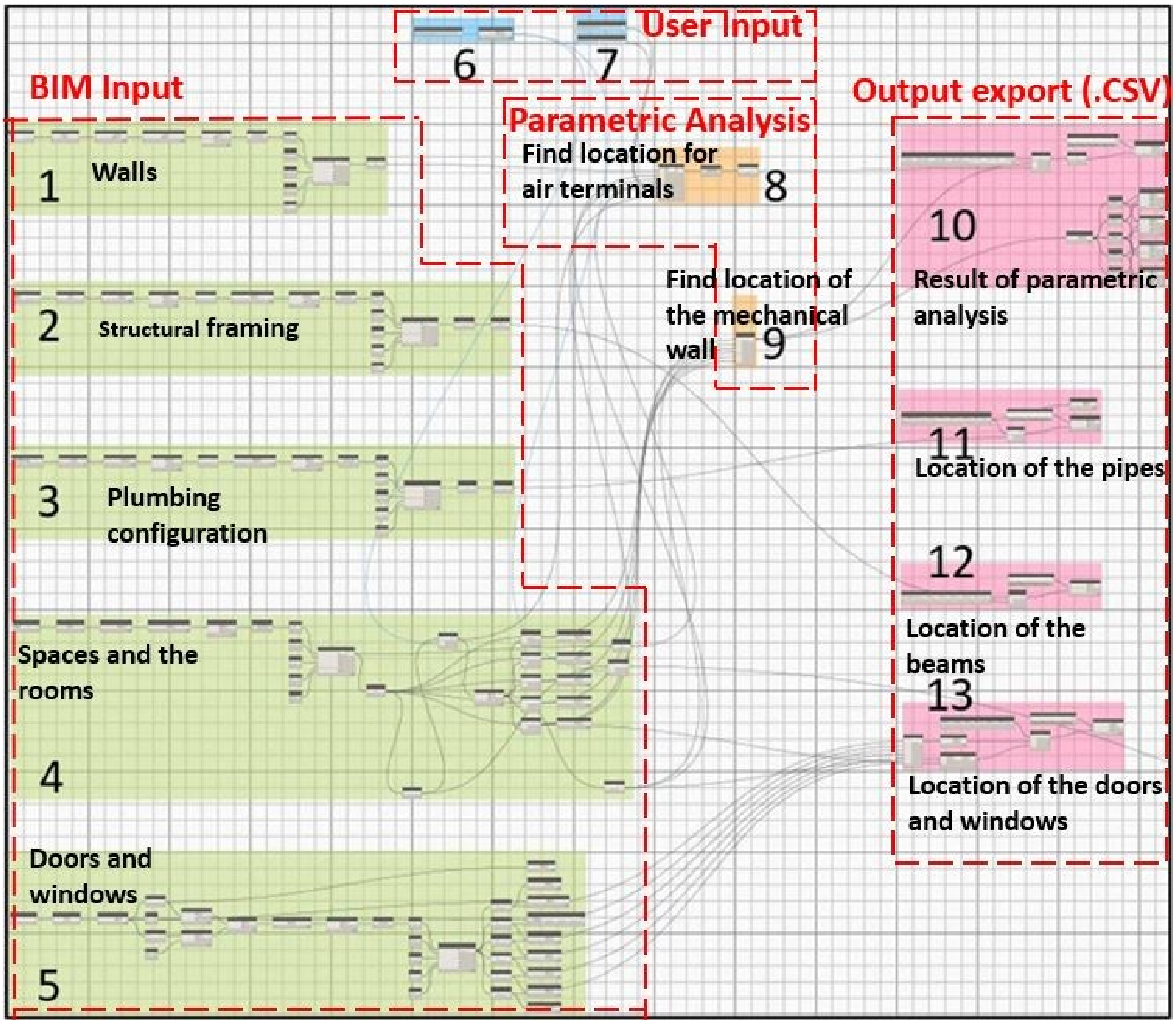


Fig. 13: Identification of the location of floor-mounted supply registers

<u>BIM-based input</u>: Blocks 1-5 are automated input blocks. They are programmed to point to specific family types such as the walls, floors, spaces, plumbing, structural system, doors, and windows, which are required for designing and the construction analysis of the air distribution design layout. These blocks are in charge of determining the bounding box that defines the position of each element in 3D space. A set of (x,y,z) coordinates will be identified that define the position of each element, for example, the relative position of a wall panel, in the model, and feed this information into the succeeding blocks. Blocks 2,3 and 5 connect to the output blocks and export the coordinates in CSV format. Blocks 1 and 5 define the wall boundaries for each room for succeeding parametric analysis blocks 6 and 9.

User input: Block number 6 allows the user to select the desired level in the building for performing the parametric analysis; each building level requires to have parametric analysis executed separately because each level varies in terms of the architectural design layout which define the rooms orientation, wall boundaries that create different spaces and the purpose of each space (e.g., bedroom, kitchen, and etc.). Block number 7 specifies the thickness required from the walls that can support the installation of the ducts; these walls will be referred to as the mechanical walls, which will be identified in succeeding block 9. The thickness of these walls should be adequate in order to support the maximum duct size that needs to be installed inside the wall.

Parametric analysis: Blocks 8 and 9 contain customized nodes programmed to perform the parametric analysis, which will be demonstrated in this chapter in detail. Block 8 is in charge of populating the air terminals in this block the appropriate locations in each space that are suitable for the installation of the floor-mounted registers will be identified and listed. Block 9 is programmed to identify the most suitable walls to be selected for the installation of the vertical ducts referred to as the mechanical wall, which will be described in more detail in section 3.1.2. Blocks 8 and 9 feed the computed data to the succeeding block 10 for exporting in CSV format.

Output exporters: Blocks 10-13 are the exporters. They are designed to export the output data in terms of (x,y,z) coordinates in CSV format. A total of four exports are made when the Dynamo code is executed. Block 10 exports the possible locations for installation of the air terminals and different candidates for the mechanical walls, which are the result of the parametric analysis blocks 8 and 9, respectively. Block 11, 12, and 13 export the configuration of the plumbing system, structural system, and the location of the doors and windows from preceding blocks 2, 3, and 5, respectively. The output files will be used for design optimization, which is discussed in section 3.2.

Summary

The logic and design requirements for determining suitable locations for the installation of the floor-mounted supply registers (Block 8) are demonstrated in this section. The selection of the mechanical walls is reviewed in subsection 3.1.2 under the details for the mechanical wall. In order to identify the optimal locations for the installation of the floor-mounted supply registers, the spatial architectural wall boundaries are fed into the custom node block 8, and the python script embedded in this node will use the data to register a series of locations that are acceptable candidates. The steps that the algorithm follows for selection of the location for installation of the floor-mounted supply registers are discussed below.

i. Multi-level analysis

Every floor in a building may include a different room layout and geometry; therefore, it is important to calculate a solution that is suitable for the selected floor layout. Block 6 in Figure 13 demonstrates the nodes that is the point of entry where the user selects the floor level for analysis via a number slider. This code block will indicate the elevation in the project model that we are working with, and it sets the constant z value for analysis of the elements associated with this level. The selected level will consist of different rooms that require supply air entry (Figure 14). Each space is identified and populated with a series of points at equal distances. Each point represents a possible location for the installation of floor-mounted registers. The purpose of the points is to provide relative (x, y, z) coordinates, which is used as an address for identifying the best location for the floor-mounted registers.

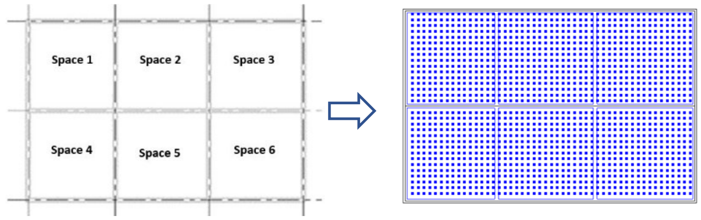


Fig. 14: The analysis of 6 rooms and their floor area

ii. Minimum distance required from the walls

Supply registers are often placed along the perimeter of each room to heat the external walls, creating a barrier to protect the building envelope from losing energy to the outside environment. However, to provide optimal air mixture, the outlets must be positioned at a specified distance from the walls to ensure relatively even and effective airflow distribution in each space. In this manner, a floor register must be installed at least 6 inches away from the walls. Figure 15 below displays the points that are adjacent to the walls being removed from the solutions candidates.

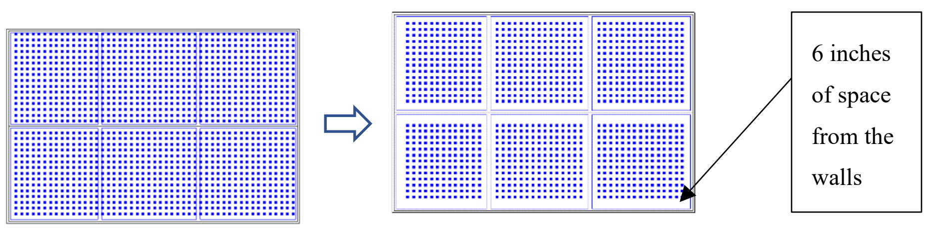


Fig. 15: A specified distance from the walls in each room

iii. Occupants pathways and usable floor area

A crucial spatial constraint imposed on the supply registers in a floor system is the pathways in which the occupants will travel. The supply air terminals should not interfere with the living space where the occupants may travel or place the furniture. The optimum location for a floor-mounted register is away from the sight and tucked away close to the room boundaries. Figure 16 below demonstrates a series of points being eliminated from the central area of the rooms.

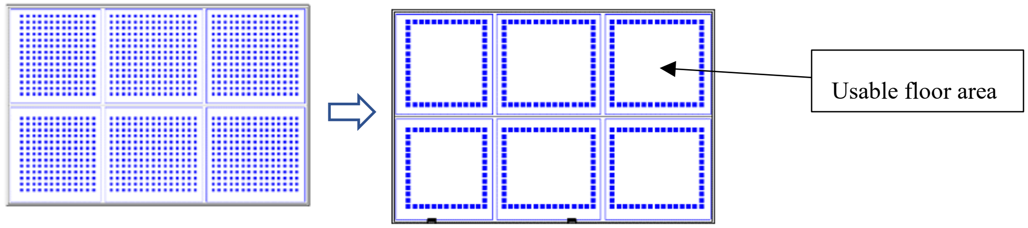


Fig. 16: The usable floor area in each room

iv. Distance from the openings (doors, windows, stairs)

The most significant source of energy loss in a building is the openings to the external environment. The windows and the doors have much less thermal resistance in comparison to the walls; therefore, the energy provided by the supply flow rate in each space can escape at a much faster rate when it is close to an opening. It is a common practice to install baseboards or linear registers that provide a barrier in front of the window openings to maintain the indoor air temperature. However, it is not cost-effective, and in most instances, a single source of supply air meets the design requirements. The proposed framework does not consider external and local heat sources (refer to suggestions for future work). Therefore, to have an energy-efficient design, it is not sufficient to place a supply air terminal directly in front of windows and doors. Figure 17 below demonstrates how the algorithm intelligently recognizes the windows and doors in the project and removes the points accordingly.

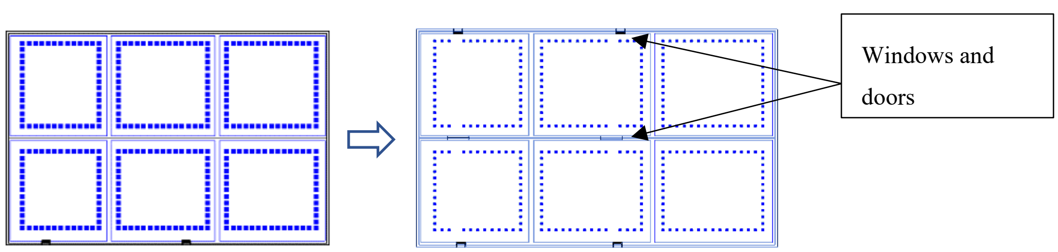


Fig. 17: Locations of the doors and windows

v. External walls and internal walls

The points adjacent to the external walls are in an unfavorable position for two reasons (i) a fast rate of energy loss (ii) far distances requiring additional ductwork.

i. The external walls will observe the energy at a higher rate because they are exposed to the outside ambient temperature. Therefore, the supplied air energy will be directly heating the walls rather than distributing the heat for the designated space. It is more practical to supply the core of the building.

ii. The air terminals located next to the building's external walls are likely to be the farthest point from our central main duct carrying the highest flow rate, which will require a long branch duct to reach all the way to these locations. Excessive length of a branch duct can affect the overall pressure balance (poor performance) as well as imposing extra material and construction work. Figure 18 below displays the location of the floor-mounted registers disappearing from the building perimeter (external walls).

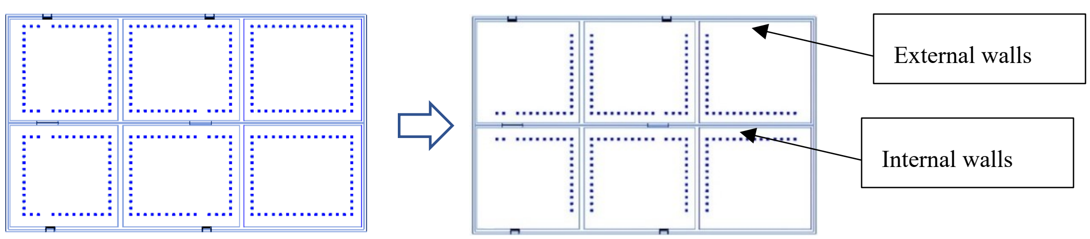


Fig. 18: External walls and internal walls

vi. Corners and confined areas

The purpose of a supply register is to diffuse the airflow rate evenly in each space. Corner points (Figure 19) are in a confined position next to two walls. In this location, a supply outlet will not perform well due to the walls constraining the distribution of the supplied air in the space.

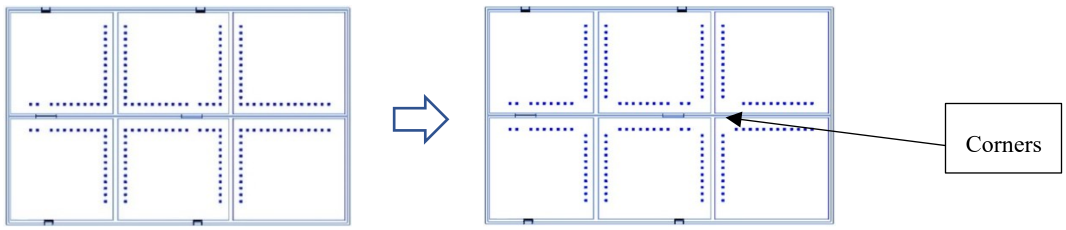


Fig. 19: Corners of each room

At this stage, all the visible spatial constraints in each space are identified and implemented in the equation. The remaining points display a series of suitable locations for the installation of the supply registers in the floor. The number of possibilities left is fewer than before; however, there must be only one location chosen for each space. Figure 20 below presents a plan view of a real-life project where the algorithm has identified suitable locations for installing floor-mounted registers for each room. 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 the optimal routes for connecting the points and creating the air distribution layout. The performance of the GA optimization is presented in section 3.2, and the final designed layout will be demonstrated in the case study section of this thesis.

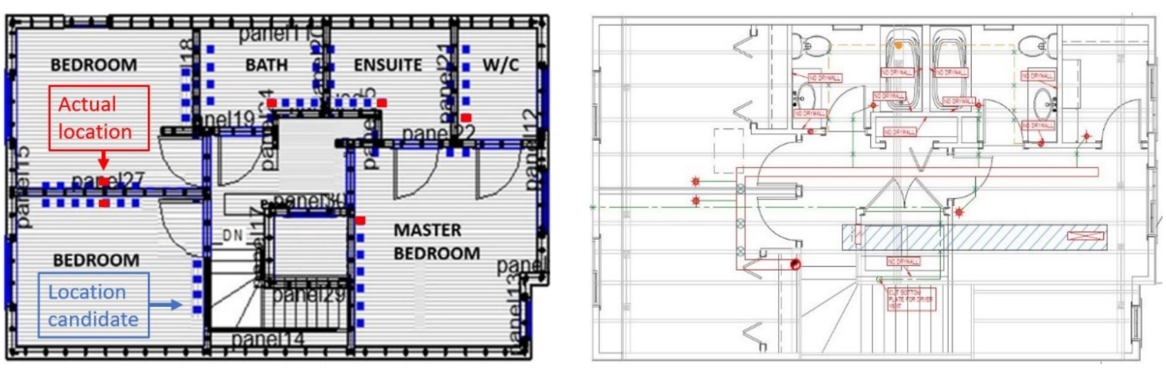


Fig. 20: Identified locations for floor-mounted supply registers

The solutions are narrowed down; nevertheless, for the best location of floor registers, the ductwork layout must be considered. The duct layout will create an air distribution network by connecting all the floor registers. There are a large number of alternative ways to connect all the points. The iteration process is done by the genetic algorithm to find the optimum solution. The final solution will consist of the most favorable position in each room to install the floor register according to the objectives dictated in the optimization section of this research. The final comparisons are made in the case study and the final chapter of this thesis.

Ceiling-mounted supply diffusers

A ceiling-mounted diffuser (Figure 21) is designed to diffuse the supply air in four directions instead of directly aiming downwards to ensure the even distribution of the air within the space. Therefore, in terms of performance, the ideal location is in the middle of the room to provide each side with equal flows. However, each space is not perfectly symmetrical, and we will often have one side of the room boundary closer to the middle. The distance to the closest wall boundary is defined as the characteristic length. There are different methods for selecting the optimum location for each diffuser in each space. The room geometry, the total number of diffusers, and their capacity play a significant role in this selection process. In this research, ADPI will be the primary design method for selecting the position for the diffusers in the designated spaces for a project model in BIM.

Fig. 21: Typical ceiling-mounted diffusers

Air Distribution Performance Index (ADPI)

ADPI is a measure that indicates how well the supplied air in a space is mixed with the existing air in the space before it exits the space boundaries. It is directly related to the occupant's comfort and designed system performance (distribution of the energy). ADPI calculation assists the designer to pick the best type of diffuser and the location for installing a diffuser to achieve optimum performance. According to [10] there are three air velocities that exist in a room with a supply diffuser.

i. $V_{k,}$ Outlet velocity: velocity of the air stream coming out of the supply outlet.
ii. $V_{T,}$ Terminal velocity: velocity that exists at the end of the diffuser throw before it hits the closest wall.
iii. $V_{R,}$ Room Velocity: velocity that exists within the room

The **throw** is the distance to the farthest point where the projected velocity remains constant before reducing. A throw of 50 ft/min (**T_{50}**) is considered for residential buildings where the occupants use the spaces adjacent to the walls. The value of the resultant velocities V_T and V_R are dependent on the diffuser's capacity, the distance from the closest wall (**characteristic length**), and the spacing between the diffusers. A V_R value of 30fpm is prescribed by ASHRAE for a comfortable room air velocity [11]. An ADPI >= 80% is considered acceptable, meaning the velocity is uniformly distributed in 80% of the space, or 80% of the occupants will be comfortable). The location for each diffuser can be calculated by finding the isothermal throw distance for the selected outlet type with using the following factors:

- Outlet Type
- Room load
- Room dimensions (L to the closest wall)
- Throw to length ratio

The following Figure 22 provides the required ratio of the throw to the characteristic length that will result in the maximum ADPI for the selected diffuser type. The two tables demonstrated in Figure 22 are from ASHRAE, Handbook, Fundamentals Volume 1997, but all manufacturers provide their ADPI selection guide catalogs. For more information in regards to the ADPI, please refer to the chapter 2 literature review.

Table 11-1 Characteristic Room Length for Several Diffusers

Diffuser Type	Characteristic Length L
High sidewall grille	Distance to wall perpendicular to jet
Circular ceiling diffuser	Distance to closet wall or intersecting air jet
Sill grille	Length of room in direction of jet flow
Ceiling slot diffuser	Distance to wall or midplane between outlets
Light troffer diffusers	Distance to midplane between outlets plus distance from ceiling to top of occupied zone
Perforated, louvered ceiling diffusers	Distance to wall or midplane between outlets

Source: Reprinted by permission from *ASHRAE Handbook, Fundamentals Volume,* 1997.

Table 11-2 Air Diffusion Performance Index (ADPI) Selection Guide

Terminal Device	Room Load, Btu/hr-ft^2	x_{50}/L^a for Maximum ADPI	Maximum ADPI	For ADPI Greater Than	Range of x_{50}/L^a
High sidewall grilles	80 (252)	1.8	68	—	—
	60 (189)	1.8	72	70	1.5–2.2
	40 (126)	1.6	78	70	1.2–2.3
	20 (63)	1.5	85	80	1.0–1.9
Circular ceiling diffusers	80 (252)	0.8	76	70	0.7–1.3
	60 (189)	0.8	83	80	0.7–1.2
	40 (126)	0.8	88	80	0.5–1.5
	20 (63)	0.8	93	90	0.7–1.3
Sill grille, Straight vanes	80 (252)	1.7	61	60	1.5–1.7
	60 (189)	1.7	72	70	1.4–1.7
	40 (126)	1.3	86	80	1.2–1.8
	20 (63)	0.9	95	90	0.8–1.3
Sill grille, Spread vanes	80 (252)	0.7	94	90	0.6–1.5
	60 (189)	0.7	94	80	0.6–1.7
	40 (126)	0.7	94	—	—
	20 (63)	0.7	94	—	—
Ceiling slot diffusers (for T_{100}/L)^a	80 (252)	0.3	85	80	0.3–0.7
	60 (189)	0.3	88	80	0.3–0.8
	40 (126)	0.3	91	80	0.3–1.1
	20 (63)	0.3	92	80	0.3–1.5
Light troffer diffusers	60 (189)	2.5	86	80	<3.8
	40 (126)	1.0	92	90	<3.0
	20 (63)	1.0	95	90	<4.5
Perforated and louvered ceiling diffusers	11–51 (35–160)	2.0	96	90	1.4–2.7
				80	1.0–3.4

^{a}For SI units, $x_{0.25}/L$ and $T_{0.5}/L$

Source: Reprinted by permission from *ASHRAE Handbook, Fundamentals Volume,* 1997.

Fig. 22: Characteristic room length and ADPI selection guide for several diffusers [10]

The following equation (3) is used for calculating the throw distance for a selected terminal device:

$$Maximium\ ADPI\ = \frac{T_{50}}{L_{Characteristic}} \qquad \text{Equation (3)}$$

Where:

- Maximum ADPI – From ADPI selection guide (>= 80% is acceptable)
- $L_{Characteristic}$ – Distance to the closest wall in the room
- T_{50} – Throw distance with a terminal velocity of 50 ft/min

The throw distance is used to determine the size of the diffuser required to satisfy the room geometrical size. The throw distance will provide a relationship between the diffuser's performance and the room boundaries. When the throw distance is calculated, it can be used to identify the positions suitable for installing the supply air diffusers knowing how effectively each diffuser will perform with their areal range of diffusion. Each room has a different characteristic length, and the information obtained from BIM will allow the calculation of the ADPI accordingly. The following example (Figure 23) demonstrates how the location of a diffuser is selected based on the calculated throw distance.

Example: A circular ceiling diffuser is selected for a room with 63 BTU/hr.ft^2 load requirement and must be positioned for achieving 93% maximum ADPI. The throw distance representing the areal range of diffusion is calculated as follows:

- From Figure 22, the ratio of T_{50} and characteristic length is obtained and must equal to 0.8 to achieve the maximum ADPI using equation 3.
- $Maximium\ ADPI = \frac{T_{50}}{L_{Characteristic}}$
- $0.8 = T_{50}/L_{Characteristic}$
- $T_{50} = 0.8 \times 7ft$
- T_{50}= 5' 8"

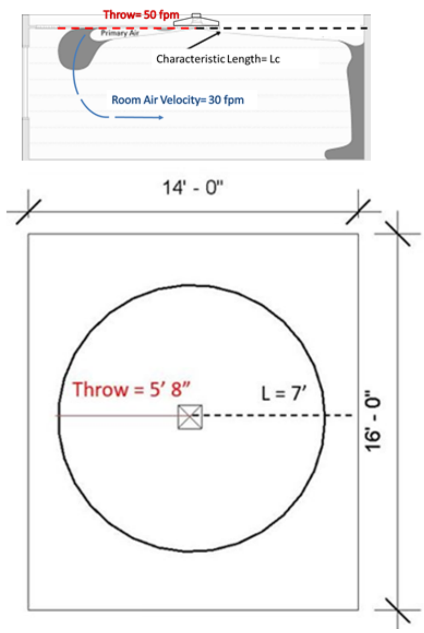


Fig. 23: Location of a diffuser with relative characteristic length and throw distance [32]

The throw distance will be used to identify suitable locations to install the diffuser. The following region [X_{max}-X_{min}, Y_{max} -Y_{min}] is adequate for installing the diffuser with respect to the throw distance (Figure 24). Within this region, the $L_{characteristic}$ is 7ft, and the parameters do not change. Anywhere inside the identified box, the diffuser can be installed while maintaining the areal range of diffusion inside the room boundaries. With this logic, the maximum ADPI remains at 93%. If space requires more than one diffuser, the distance between 2 diffusers must be 2x the throw distance.

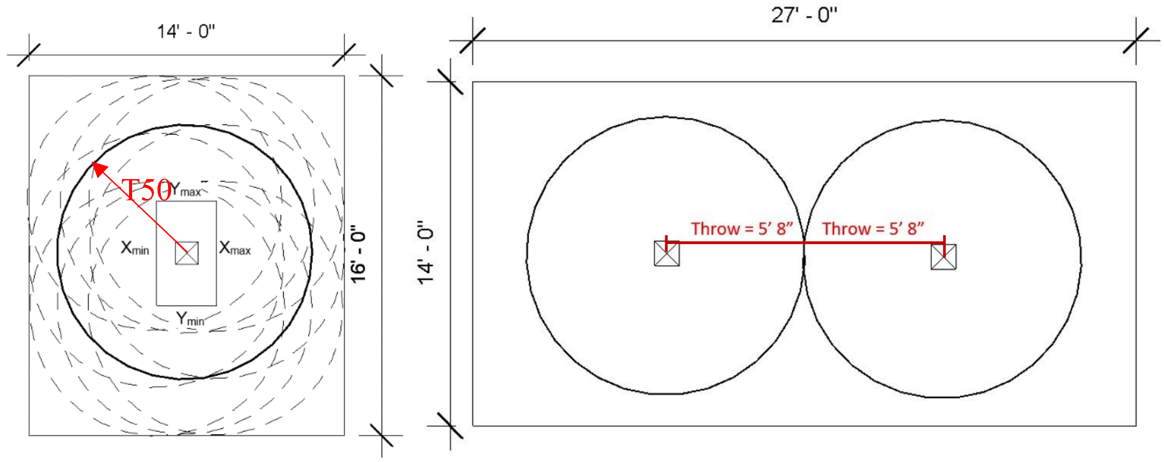


Fig. 24: Positioning and spacing of air terminals according to the throw distance

The algorithm for analyzing the Revit model was designed as a series of custom nodes in Dynamo Add-in for Revit with some input ports and output ports. Each custom node is preceded by an input such as family types, and it is programmed to compute the required data from the specified building elements. In this section, the different blocks that form the script will be reviewed with more detail, which can be useful for future development. The following Figure 25 illustrates a snapshot of the created code in Dynamo (version 2.1.0). The algorithm is designed for discovering the optimal location for the installation of the ceiling-mounted diffuser and has 17 main blocks. The blocks are divided into three categories, 1-5 are automated input block, 6-7 are user-adjustable inputs, 8-

13 are processing block, and 14-17 are output blocks. The relationships between blocks are demonstrated below.

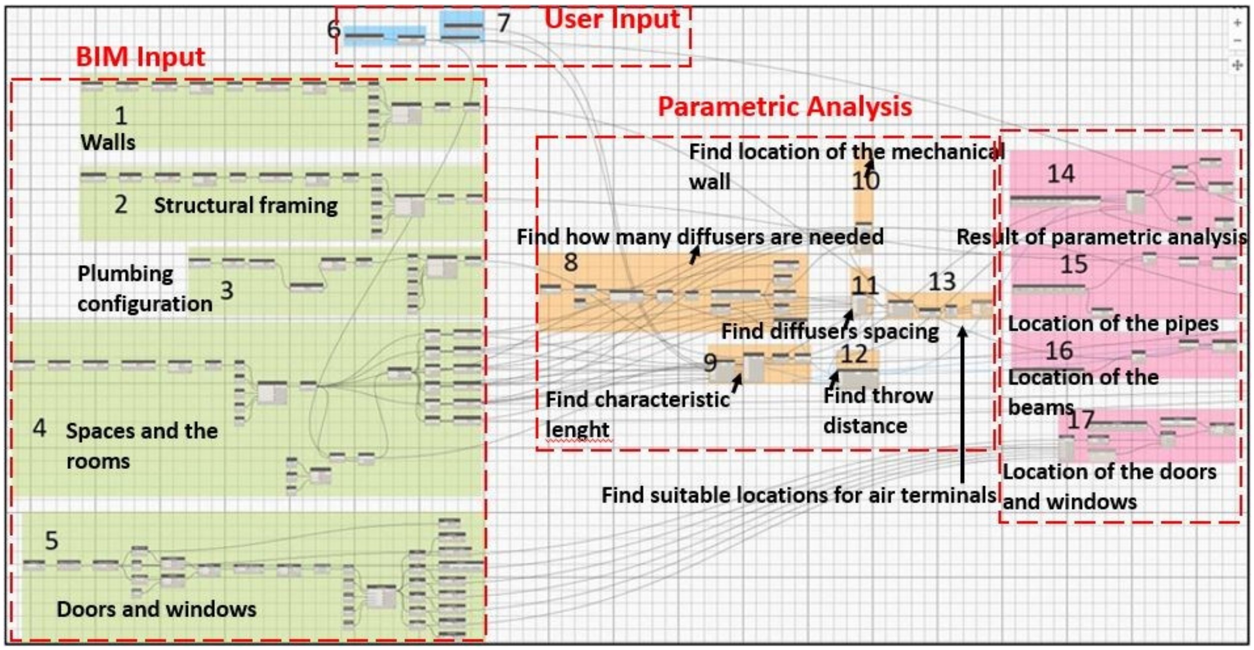


Fig. 25: Identification of the location of ceiling-mounted supply diffusers

BIM-based input: Blocks 1-5 are automated input block. They are programmed to point to specific family types such as the walls, floors, spaces, plumbing, structural system, doors, and windows, which are required for the design and construction analysis of the air distribution design layout. These blocks are in charge of determining the bounding box that defines the position of each element in 3D space. Maximum x.y and z coordinates that define the position of each element are extracted from the model and fed into the next blocks. Blocks 2,3 and 5 connect to the output blocks and export the coordinates in CSV format. Blocks 1 and 5 define the wall boundaries for each room for succeeding parametric analysis blocks.

User input: Block number 6 allows the user to select the desired level in the building for performing the parametric analysis; each building level requires to have parametric analysis executed separately because each level consists of a different architectural layout. Block number

7 specifies the thickness required for the mechanical wall, which will be used in succeeding block 9 for finding the suitable walls for installation of the vertical duct segments; the thickness should be enough to support the maximum duct size that needs to be installed inside the wall.

Parametric analysis: Blocks 8-13 contain customized nodes programmed to perform the parametric analysis, which will be demonstrated in this chapter in detail. Block number 10 is in charge of calculating the characteristic length for each room based on the room and wall boundaries received from preceded blocks 1 and 4. Block 11 calculates the throw distances, T, using equation (4), and the characteristic length found in block 10. Block 12 assigns the spacing between the diffuser based on two times the throw distance found in block 11, and block 13 identifies the permissible boundaries for the installation of the ceiling-mounted diffusers in each space using the associated room boundaries from block 1 and 2 and the identified throw distances. Block 9 is programmed to identify the most suitable walls to be selected for the installation of the vertical ducts referred to as the mechanical wall, which will be described in more detail in section 3.1.2. The result of the blocks 13 and 9 are exported in the succeeding block 14.

Output exporters: Blocks 10-13 are the exporters. They are designed to export the output data in terms of x,y,z coordinates in CSV format. A total of four exports are made when the Dynamo code is executed. Block 14 exports the possible locations for installation of the air terminals and possible mechanical walls, which are the result of the parametric analysis blocks 8-13. Block 15, 16, and 17 export the configuration of the plumbing system, structural system configuration, and the location of the doors and windows from preceding blocks 2, 3, and 5.

Summary

The developed algorithm behaves the same as the one for floor-mounted supply registers in terms of the input and output functions. However, the computational nodes for locating the optimal location for the installation of the ceiling-mounted diffusers are different. In this section, the step-by-step process of implementing the ADPI design factor in the trained algorithm will be demonstrated. The selection of the mechanical walls is reviewed in subsection 3.1.2 under the details for the mechanical wall.

Step 1

The first step is to locate the center of each room that requires a supply air outlet (Figure 26),

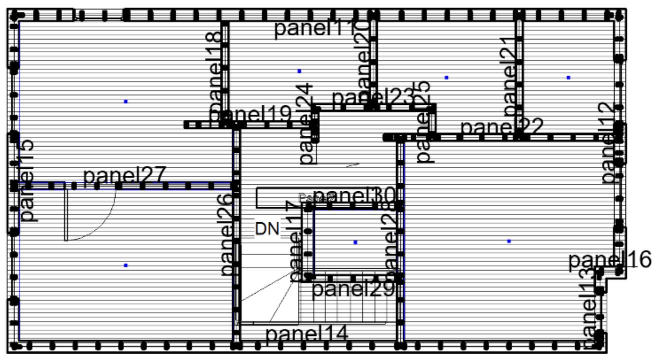


Fig. 26: The center of each room with a blue point

Step 2

Blocks 10 and 11 are programmed to find the characteristic length of each room (closest distance to a wall from the center point) and to calculate the throw distance based on a given maximum ADPI value and the identified characteristic lengths (equation 3). The following Figure 27 demonstrated the areal range of diffusion known as the throw distance for each diffuser in plan view.

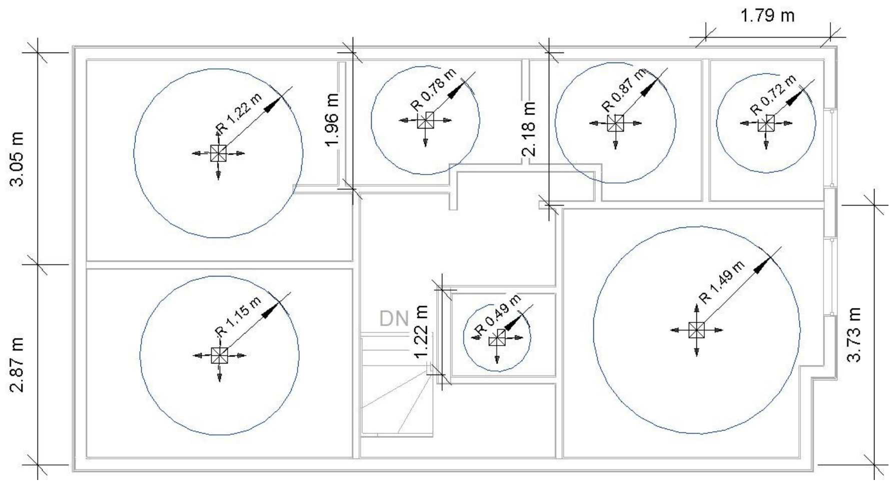


Fig. 27: The range of diffusion for each diffuser

Step 3

Each space has a different required flow rate, which will determine the type, the size, and the total number of diffusers required to meet the space needs. Each room in the BIM project contains data, including the load requirements. Based on the selected diffuser and their capacities, the developed algorithm will determine how many diffusers need to be placed in each space. The distance between two adjacent diffusers will be equal to 2xT_{50}. The custom nodes for evaluating the number of diffusers and their spacing are blocks 8 and 11. The following Figure 28 demonstrates the spacing between diffusers if more than one diffuser is required to be installed in a room with a bigger floor area.

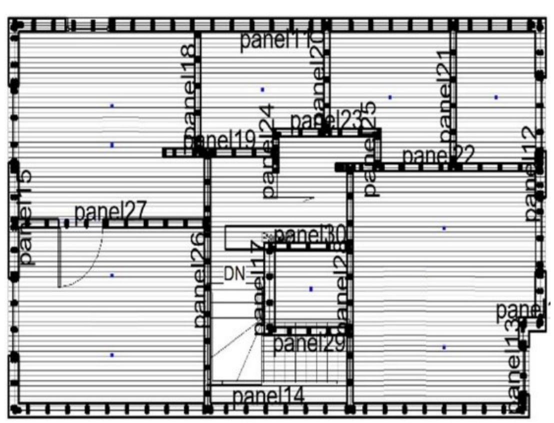


Fig. 28: Space between air terminals (blue points)

The location for each diffuser is identified, and the range of flexibility for installation is determined. Each diffuser can be placed inside of a box calculated with respect to the areal range of diffusion. In order to determine the final position of the ceiling-mounted diffusers, the ductwork layout and accessibility for construction must be considered. The ductwork layout will create an air distribution network by connecting all the diffusers together. The remaining challenge is determining the best layout configuration for the system, which will be covered in the design optimization section of this chapter. Design optimization (section 3.2) will demonstrate the objectives used to create the optimum layout and the final position of the diffusers.

Return air system

The primary purpose of the return air system is to recirculate the supplied air, exhaust the used air mass, and provide a pressure balance in the building enclosure. In practice, the return air inlets are positioned as far as possible from the supply air outlets to avoid short-circuiting the conditioned air and provide adequate time for the supplied energy to be distributed in the building before it is capture and returned to the central air handling unit. In this research, two modes of commonly used ventilation systems in residential buildings are applied.

1. Mixing ventilation
2. Displacement ventilation

Fig. 29: Ceiling vents for mixing ventilation

Fig. 30: Sidewall vents for displacement ventilation [30]

Mixing ventilation is suitable for heating and cooling applications (Figure 29). To create an HVAC network consisting of mixing ventilation, the supply air outlet, and the return air inlets must be installed in the ceilings. The supplied air is injected into the rooms at a higher velocity and mixed with the existing air. It is gradually extracted and ventilated by the return vents, which are usually installed in the corners.

Displacement ventilation (Figure 30) 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 are positioned on sidewalls. This will allow the supplied air mass to gradually distribute the energy in each space and mix with the existing air in the room as it rises towards the ceiling. The room air is gradually extracted and ventilated through the return air terminals, which are often positioned in the corridors and walkways. Figure 31 below demonstrates displacement ventilation applied in a 3D model.

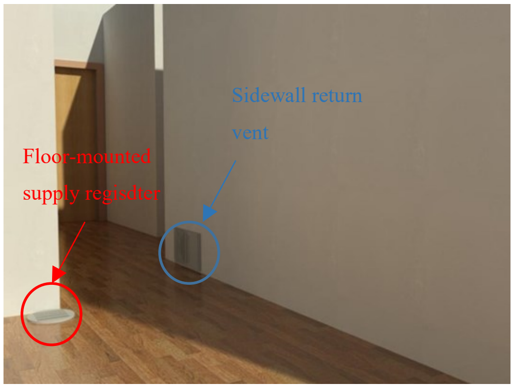


Fig. 31: 3D rendering of a floor register and a side wall return vent in Revit (displacement ventilation)

Based on the mixing ventilation requirements, the supply system will consist of ceiling-mounted diffusers. The position of the return inlets will be according to the position of the supply air outlets. The return vent must be placed in the farthest location away from all the supply diffusers (Figure 32). The path that the supplied air travels must be far enough to allow an adequate circulation and mixing of the air within the space before the air stream reaches the return inlets and exits the zone.

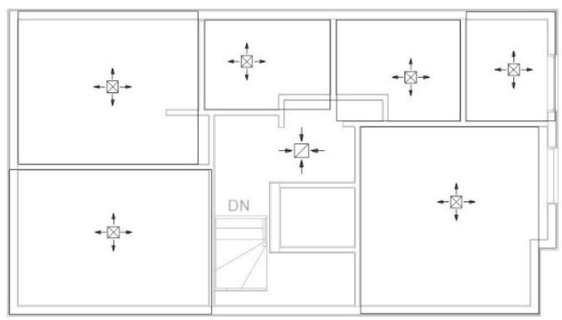


Fig. 32: The position of supply and return air terminals for mixing ventilation in Revit

Depending on the space flow requirements, the flow in must equals the flow out of each zone to provide a net-zero pressure inside the building enclosure. The supplied air must be distributed and cover all the floor area. Therefore, the total number of supply outlets is more than the return air inlets. The building enclosure must consist of a balanced pressure, and all the supplied air must be ventilated. The supply air network is more complex, with many branch ducts supplying each room; however, the capacity and the size of the supply outlets are smaller than the return air system. The supply outlet consists of smaller ducts as compared to the return air system with larger ducts and a higher intake flow rate at each air terminals.

The algorithm for analyzing the Revit model was designed as a series of custom nodes in Dynamo Add-in for Revit with some input ports and output ports. Each custom node is preceded by an input such as family types, and it is programmed to compute the required data from the specified building elements. In this section, the different blocks that form the script will be reviewed with more detail, which can be useful for future development. The following Figure 33 illustrates a snapshot of the created code in Dynamo (version 2.1.0). The algorithm is designed for discovering the optimal location for the installation of the return air grills in sidewalls and contains 13 blocks. The blocks are divided into three categories, 1-6 are automated input block, 7-8 are user-adjustable inputs, block 9 is the processing block, and 10-13 are output blocks. The relationships between blocks are demonstrated below.

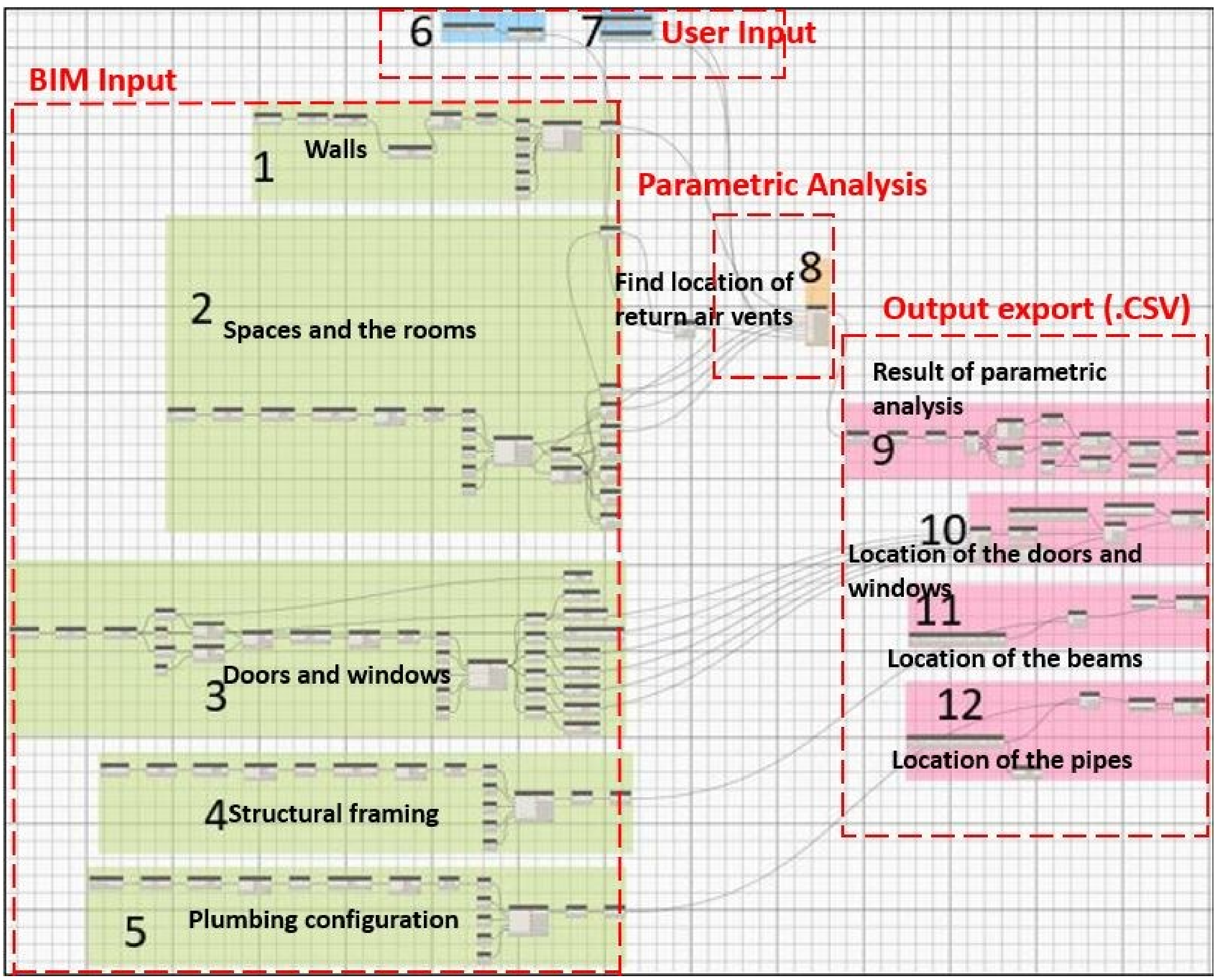


Fig. 33: Identification of the location of return air terminals

BIM-based input: Blocks 1-5 are automated input block. They are programmed to point to specific family types such as the walls, floors, spaces, plumbing, structural system, doors, and windows, which are required for the design and construction analysis of the air distribution design layout. These blocks are in charge of determining the bounding box that defines the position of each element in 3D space. Maximum x.y and z coordinates that define the position of each element of extracted from the model and fed into the next blocks. Blocks 3,4 and 5 connect to the output blocks and export the coordinates in CSV format. Blocks 1 and 2 define the wall boundaries for each room for succeeding parametric analysis blocks.

User input: Block number 6 allows the user to select the desired level in the building for performing the parametric analysis; each building level requires to have parametric analysis executed separately because each level consists of a different architectural layout. Block number 7 specifies the thickness required for the mechanical wall, which will be used in succeeding block 9 for finding the suitable walls for installation of the vertical duct segments; the thickness should be enough to support the maximum duct size that needs to be installed inside the wall.

Parametric analysis: Block 8 contains customized nodes programmed to perform the parametric analysis, which is demonstrated in this section in detail. This block is in charge of determining the appropriate sidewalls or the ceiling space that is suitable for the installation of the return air grills. If displacement ventilation is selected, the mechanical wall will host the return air grill. If the mixing ventilation is selected, the ceiling space within the building corridor adjacent to the mechanical wall will be selected as the candidate location for the installation of the return air vent. The preceding blocks are 1 and 2, which define the location of the walls and the rooms that are supplied with air; therefore, the return inlet must be position in the corridor, which is not specified as a room and is in a centralized location.

<u>Output exporters</u>: Blocks 9-12 are the exporters. They are designed to export the output data in terms of x,y,z coordinates in CSV format. A total of four exports are made when the Dynamo code is executed. Block 9 exports the possible locations for the installation of the return air terminals, which is the result of the parametric analysis blocks 8. Block 10, 11, and 12 export the configuration of the plumbing system, structural system configuration, and the location of the doors and windows from preceding blocks 3, 4, and 5.

Summary:

For residential buildings, centralizing the return air system within the building's corridors will allow the supply airflow to circulate in each room and find its way out towards the central corridors prior to ventilation. The return air system will be designed after the supply system is set in place. The return air network will be less variable with fewer possibilities as to where the air terminals can be positioned for optimum performance. Block 8 demonstrated in (Figure 33) is introduced to find the optimal location for the return air terminal in Dynamo. The input for this node is the relative position of the supply air terminals (the rooms with supply air outlets), suitable walls within the building corridors, the thickness of the wall required, and the floor level that requires a return air system. The criteria set in place is selecting the face of the walls that point toward the corridor and selecting them as a candidate location for installation of the return air grills. As mentioned, the return air terminal will be located in this corridor of the building and installed on a suitable wall if the displacement ventilation is used. If the mixing ventilation is chosen by the user, the return air terminal will be placed on the ceiling above the chosen walls. The output of this node is the x,y,z coordinates that define alternative locations for return air terminals.

3.1.2 Air Distribution Network Layout

After the location for the supply and return air terminals are determined, the remaining challenge is connecting the system via ductwork inside the floors and the walls. In order to be cost-effective, the ductwork layout must consider the shortest paths. At the same time, spatial constraints must be identified and considered. This section reviews the process for calculating the ductwork layout configuration and the associated length of the system. The horizontal layout will be developed in accordance with the floor area, and the vertical duct segments will be design based on the mechanical wall selection.

Ductwork layout components

Centralized air distribution systems can be seen as large tree-networks of supply and return air ducts connecting the network consisting of many different air terminals. Once the location for all the air terminals has been 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:

i. **Main ducts:**

- Largest duct carrying the highest flow rate from the central air handling unit to each floor
- Horizontal main duct is centralized on each floor to reach both sides of the building.
- Vertical main ducts connect each floor and are installed in the mechanical walls.

ii. **Branch ducts:**

- Smaller in cross-section
- Delivers the airflow required from the main duct to the diffusers in each space

When considering a ductwork network, initially, the appropriate route for the main duct carrying the highest flow rate must be determined. The main duct is often placed along the building corridors or the centreline of the building to have almost equal distance from farthest air terminals in both directions; this creates a more balanced system in terms of pressure drop 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.

Air distribution system's layout

The connection of the air terminals determines the layout of the air distribution system. This section will demonstrate how the total length of the ducts is mathematically calculated using the input points that are associated with the location of each air terminal. In the following Figure 34, the endpoints demonstrate the location of the air terminals. The average distance between all the points will define the position of the main duct, which will be in the center of the given floor. Each endpoint is required to be connected to the main duct via a branch duct. The point of intersect between the endpoints and the main duct is referred to as the midpoint point. The distance between the endpoints and the midpoint will equal to the length of the branch duct section (duct path). The length of the main duct is calculated based farthest location of the air terminals. The endpoints that are located at the farther location along the building axis will be used to calculate the length of the main duct. Accordingly, the length of the main duct is equal to the distance between the X_{max} and the X_{min} if the longest building axis is in X-direction or it will be equal to the distance between the Y_{max} and Y_{min} if the longest building axis is in the Y-direction (the building plan in Figure 34 has the longest axis in the Y-direction). The branch duct will connect to the main duct via 90-degree angles. The total length will be calculated by the sum of all the branch ducts plus the length of the main duct. The Figure 34 below demonstrates a simple example of a generic tree branch duct network and the relative calculations for the total length.

a)

Endpoints	n	x	y	z
A.T	1	-10	35	1
A.T	2	-2	35	1
A.T	3	-10	20	1
A.T	4	-2	20	1
A.T	5	-10	5	1
A.T	6	-2	5	1
M.W	7	-2	10	1

Main duct	x	y
Y-max (starting point)	-6	35
Y-min (end point)	-6	5

Midpoints	x	y
A	-6	35
B	-6	20
C	-6	10
D	-6	5

b)

Endpoints	n	x	y	z
A.T	1	35	-10	1
A.T	2	35	-2	1
A.T	3	20	-10	1
A.T	4	20	-2	1
A.T	5	5	-10	1
A.T	6	5	-2	1
M.W	7	10	-2	1

Main duct	x	y
X-max (starting point)	35	-6
X-min (end point)	5	-6

Midpoints	x	y
A	35	-6
B	20	-6
C	10	-6
D	5	-6

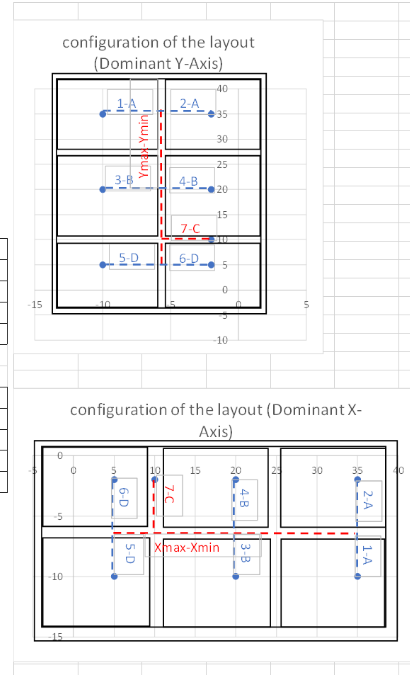


Fig. 34: Air distribution system layout with associated duct paths a) building orientation along y-axis b) building orientation along the x-axis

The equation for calculating the branch duct lengths:

$$\sum L_{branch} = \sqrt{(X_n - X_{midpoint})^2 + (Y_n - Y_{midpoint})^2} \qquad \text{Equation (4)}$$

The equation for calculating the main duct length :

$$L_{main} = (X_{max} - X_{min}) \;\text{ or* }\; L = (Y_{max} - Y_{min}) \qquad \text{Equation (3)}$$

*Depending on which axis is along the longest direction of the building

- L_{Branch} – Length of the branch duct path
- L_{Main} – Length of the main duct path

The vertical segment of the main duct will be installed inside the mechanical walls. The vertical ducts are responsible for carrying the required flow rates between each level of the building. The length of the vertical duct is equal to the difference of elevation between each level.

3.4.2 Mechanical wall

The vertical duct carrying air from floor-to-floor is embedded in one of the interior walls. The wall which carries this vertical duct is referred to as the mechanical wall. The main duct carries the highest flow rate and is responsible for delivering to each space in the project; therefore, it must reach every level that consists of space heating, cooling, and ventilation inquiries. The selection of a mechanical wall must be based on the identified parameters to ensure the safety, stability, and functionality of the air distribution system. This section will review the step-by-step process of selecting the best mechanical wall within the project. The algorithm will identify all the walls in a project and eliminated the ones that are not adequate.

i. External walls

The walls creating the parameter of the building which are exposed to the outside atmosphere are referred to as the external walls within this section. Although these walls are easy to access for construction from outside, they are eliminated from our solution due to the extreme thermal exposure through convection, which can cause freezing or high rate of energy loss from the duct system.

ii. Interior walls

The main duct on each floor is often laid in the center of the building along the longest axis. There are a starting point and an endpoint associated with the vertical segments of the main duct. The starting point is the vertical connection to the level below, and the endpoint is the vertical connection to the next level. To simplify the equation, the walls that exist close to the last air terminal will be good candidates to be the mechanical walls. In this manner, the main duct is not required to turn back to connect to a mechanical wall, which is in the center. The main duct will connect to the mechanical wall via a single 90-degree turn. Reducing the number of turns that the main duct is subjected to will create a simpler construction process. The optimization algorithm is responsible for determining which walls will require the minimum ductwork in the installation of the layout.

3.1.3 Spatial Constraints

In the initial design of the air distribution layout, some indirect variables, such as the existing architectural and plumbing features, will impose physical restrictions on the layout solution. If all the details in the projects are not considered and factored into the problem from the initial stage, unexpected problems will occur during construction, and rework will be required. For example, if a preliminary route from the main duct has an obstacle interfering with the path such as a beam, then a different and possible longer path will be chosen. Additional ducts will affect the pressure balance in the system, and it will require updates to be made in the design pressure calculation from the engineer; also, it will require additional construction time and material from the contractor in charge. It is important to solve design conflicts with an intelligent solution to avoid excessive waste in material and time.

When considering a network layout, there are constraints such as structural elements and other building systems that may interfere with the selected paths. Therefore, a viable design must consider how the branches connect to the main duct, and how the main ducts on each floor connect with each other, thereby creating a fully functioning system within the project space that will be the same during the design and construction. This section will precisely cover the physical constraints that exist in the BIM project. The physical constraints identified will directly influence the decision-making process for creating the air distribution layout. Prior to implementing the proposed algorithm, the following spatial constraints are identified and extracted from the BIM environment.

Structural Constraints

The structural system, including the beams and the columns, dictates the boundaries that the ductwork can be installed. This section identified the structural constraints imposed on the air distribution system layout. A common method for separating the building system from the structural members is creating a drop ceiling (fake ceiling). However, drop ceilings are not always ideal because it takes away from the space in the room, and the minimum height required for a living space is 7ft 6" inches which cannot be reduced by law. Usable space will add beneficial effects to the quality and value of the building. Therefore, the MEP system may have to be installed in the same elevation as the structural beam systems. In this scenario, extra rough-in work is required to either, puncture holes into the beams, or extend the length of the system by changing the direction and taking a longer path. Either way, this challenge will require extra work and more MEP pipes, ducts, or conduits. With integrated decision-making process where all of the elevations of the structural members and the MEP systems are included in the equation, calculated planning can be done to ensure minimum conflict exists between the systems and the building structure for faster installation time and save in the ducts, pipes and the conduits which can add up to a great saving in the entire project.

i. Structural framing system

The structural components of a given building project impose a constraint on the routing of the MEP system. An air distribution system must be in accordance with the structural system. Floor framing and the direction of the beam system must be considered prior to the design of the air distribution layout. If the direction of the beam system is not considered, the path of the duct system layout may be interfered with, and punch holes are required to be made in the beams. Punch holes in the beams can impose a longer construction time, damage to the structural integrity, more construction waste, and difficult access for repairs. If the planned routing solution interferes with a critical structural member such as columns and stairs, it will require rerouting and need for a change order that will be time consuming and inefficient.

ii. Floor framing

A floor system can consist of a concrete slab or wood/steel framing. The concrete floor system is much less flexible, and once cured in place, the trade workers cannot puncture through it only for a branch of the duct. Therefore, coordinated plans must be made to avoid any interferences between the two systems. A wood framing structure (Figure 35) is flexible in terms of embedding the HVAC system. The spacing between the joists will provide a plenum space for installing the ducts. However, each turn in the duct path will require a punched hole with a clearance of 0.5 inches to run the duct through the structural wood member. Depending on the depth of the beams/joist, the trade workers are limited to the number and the sizes of the holes they are allowed to make inside the structural framing. Open joist trusses are more flexible for running the building systems; however, they are more expensive and not always the practical choice.

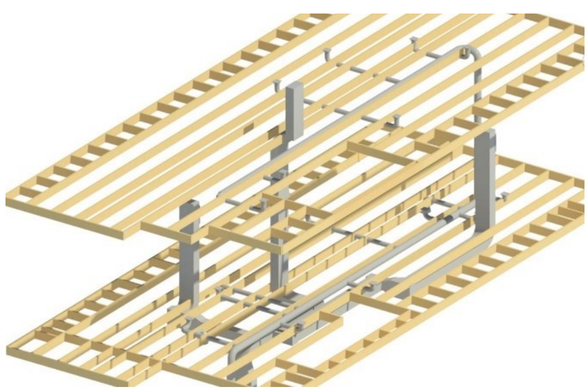


Fig. 35: Correlated ductwork layout with respect to the wood framing structure (Revit)

iii. Wall framing

The walls in the project consist of horizontal and vertical studs supporting the structure of the building. Whether they are retaining walls, load-bearing walls, shear walls with cross bracing members, or simple partition walls, they all vary in the level of importance and the constraints they impose on the design of the air distribution system layout. The selection of a mechanical wall in the previous section highlights the constraints and parameters in selecting the right walls for embedding the ductwork. However, the selected walls will consist of framing members; therefore, the same technique will be applied in minimizing the number of holes required in the structural members. The optimization algorithm is in charge of creating a system with minimum conflicts with the building structure.

MEP Constraints

Building construction is an interdisciplinary project. The mechanical, electrical, and plumbing systems are crucial for creating a comfortable living environment, and poor design in any of the categories will directly influence the value and the quality of the project. The coordination of the building systems from the planning stage will allow the systems to be developed accordingly without any conflicts and constructability issues. The MEP elements in the building will co-exist along with the ductwork in the same plenum spaces. In this research, the plumbing elements are identified as a constraint limiting the pathways for the installation of ducts.

Plenum spaces in the ceiling voids are identified to be suitable for hiding away the building system from plain sight. Due to the different purposes for each building system, they will have variation in terms of installation height and the part of the building they serve. The air distribution system is the primary domain of this research and is identified as the most expensive building system. The ductwork must start from the central air handling unit and reach every space in the building requiring HVAC. The path in which the ductwork is installed shall not conflict with major pipeline or electrical junctions.

If the schematics drawing for the plumbing and other building elements are defined prior to the design of the air distribution system, the optimal layout can be determined accordingly to prevent congested areas and conflicting designs. In this research, the existing plumbing elements in the project are identified as another constraint that must be avoided when designing the ductwork layout (Figure 36). The trained algorithm automatically calculates the preliminary duct layout; therefore, each time an intersection or an overlap occurs with the existing MEP element, the algorithm will consider a different solution to avoid as many clashes as possible.

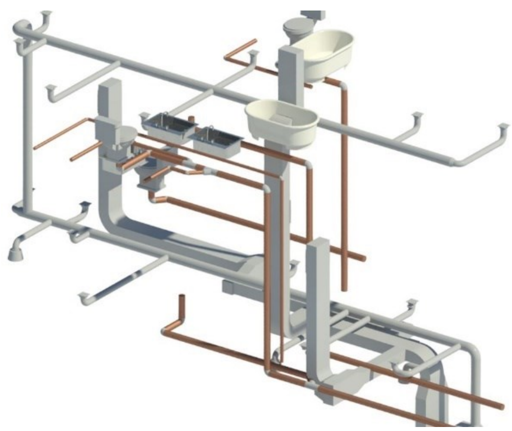


Fig. 36: Correlated ductwork layout with respect to the plumbing system configuration (Revit)

3.2 Design Optimization

The second procedure in the proposed methodology is the design optimization of the air distribution system layout. In this section, the data from the previous parametric analysis modules are processed in a tailored genetic algorithm to discover different design alternatives and generate the optimal design layout. In this chapter, the genetic algorithm (GA) is introduced as an optimization technique for solving the challenges regarding the design and construction of the air distribution system layout for modular construction. This chapter will review the process of training this algorithm to solve the HVAC design challenges in the BIM environment to increase the means for constructability and prefabrication. Python is the selected programming language to implement the algorithm [29]. The input for this algorithm is the extracted parameters from the BIM, and the output is an optimum ductwork layout configuration.

The previous section demonstrated the parametric analysis modules developed to extract the design parameters from BIM. The information extracted is in CSV format and is ready to be fed into the optimization algorithm for further analysis and development of the design solutions. The input data defines the design constraints and provides the range of x,y,z coordinates required for determining the location of the air terminals and the ductwork layout configuration. The optimization algorithm will assign a single position for each air terminal and discover the routes that are acceptable 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.

There are three objectives in the optimization algorithms which are selected to improve the constructability of the ductwork layout by increasing the design efficiency and accuracy. The proposed objectives are construction-related in order to help reduce conflicts, material wastage, and reduce the project duration. The multi-objectives selected for optimization are described in detail in this section. The design criteria discussed in the previous section for placement of the air terminals for efficient performance are set as constraints to ensure the final solution is in compliance with the design requirements and meets a quality performance. The result of the design optimization algorithm is a set of x, y, z coordinates. The output includes the final location of the air terminals and the ductwork layout configuration relative to the chosen floor and wall panels for installation. The final step is to transfer this information back into the BIM model, which will be covered in 3D visualization section 3.3. The output of the design optimization algorithm will be a complete mathematical model of the air distribution layout, which is correlated with the project's physical model and is cost-effective and ready to be transferred back into the BIM environment.

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 provide 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. There are three objectives in the optimization algorithms which are selected to improve the constructability of the ductwork layout by increasing the design efficiency and accuracy. The construction-related objectives are set as penalty objectives in order to help reduce conflicts and material wastage. The design criteria discussed in the previous section for placement of the air terminals for efficient performance are set as constraints to ensure the final solution is in compliance with the design requirements and meets a quality performance.

In this research, GA considers the following objectives and constraints:

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

Fitness Function

The fitness function is used to evaluate the different solutions generated by the tailored GA algorithm. The defined fitness function includes three measurable and weighted variables. The first variable is (L), which measures the total length of the duct system. The solution consisting of the shortest total length is the most desirable. The two other measurable objectives are the intersection of the ductwork with the structure and MEP elements. These objectives are identified to increase project duration; therefore, they must be reduced to improve the constructability in offsite construction. The fitness function evaluates the total system interferences for each solution, the solution with the least intersection with the structural elements, and the existing MEP system 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 evaluation of the fitness value. 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 them. The fitness function used to evaluate the result of the algorithm is represented below as equation (6):

$$Fitness\,Value = -(W_1) \times Length + -(W_2) \times MEP\ Conflicts + -(W_3) \times Structural\,Interference$$

Equation(6)

Where:

- Length – Is measured in ft or meters based on the project model
- MEP Conflicts – Each intersection of the duct and MEP element counts as one
- Structural Interference – Each intersection of the duct and structural element counts as one
- W – Percentage weight assigned to the variable

Distributed Objective Weights

The weight of each objective must be assigned based on the total time it imposes on the project duration. Off-site construction requires standardized design and a series of sequential tasks aimed at reducing variance in the processing time of each activity on the manufacturing line. Accordingly, each of the tasks must be closely monitored and timed during the installation of the ducts to achieve the average time associated with each objective for the proposed fitness function. In this manner, the project managers can predict the most time-consuming tasks and assign more weights to the associated objectives in order to modify their designs and reduce variation in construction time.

3.2.1 Problem Formulation

Each space has finite locations in which an air terminal can be installed. The previous chapter reviews the process of selecting a series of suitable locations for installing air terminals in the 3D project model based on the practical industrial approach and the design point of view. In order to complete the design of the air distribution system, all the air terminals need to be connected to branch ducts, and the branch duct needs to be connected to a main central duct to create the final layout. There are a large number of combinations of how the branch ducts and the main ducts can be connected to create a layout solution. Generating every single possible solution will require millions of iterations, which is not practical; therefore, GA is utilized as an evolutionary algorithm to discover the path towards the best solution with adequate processing time. Implementing GA makes it possible to locate the optimal position for an air terminal in each space, assess the shortest ductwork layout required to connect the system, and further eliminate interferences with structural and existing MEP elements to determine the most optimum solution. The proposed algorithm is represented as a flowchart in the following Figure 37, and all steps are discussed in detail in the next paragraphs for mathematically designing the air distribution system layout. The output of the design optimization algorithm will be a complete mathematical model of the air distribution layout, which is correlated with the project's physical model and is cost-effective and ready to be transferred back into the BIM environment.

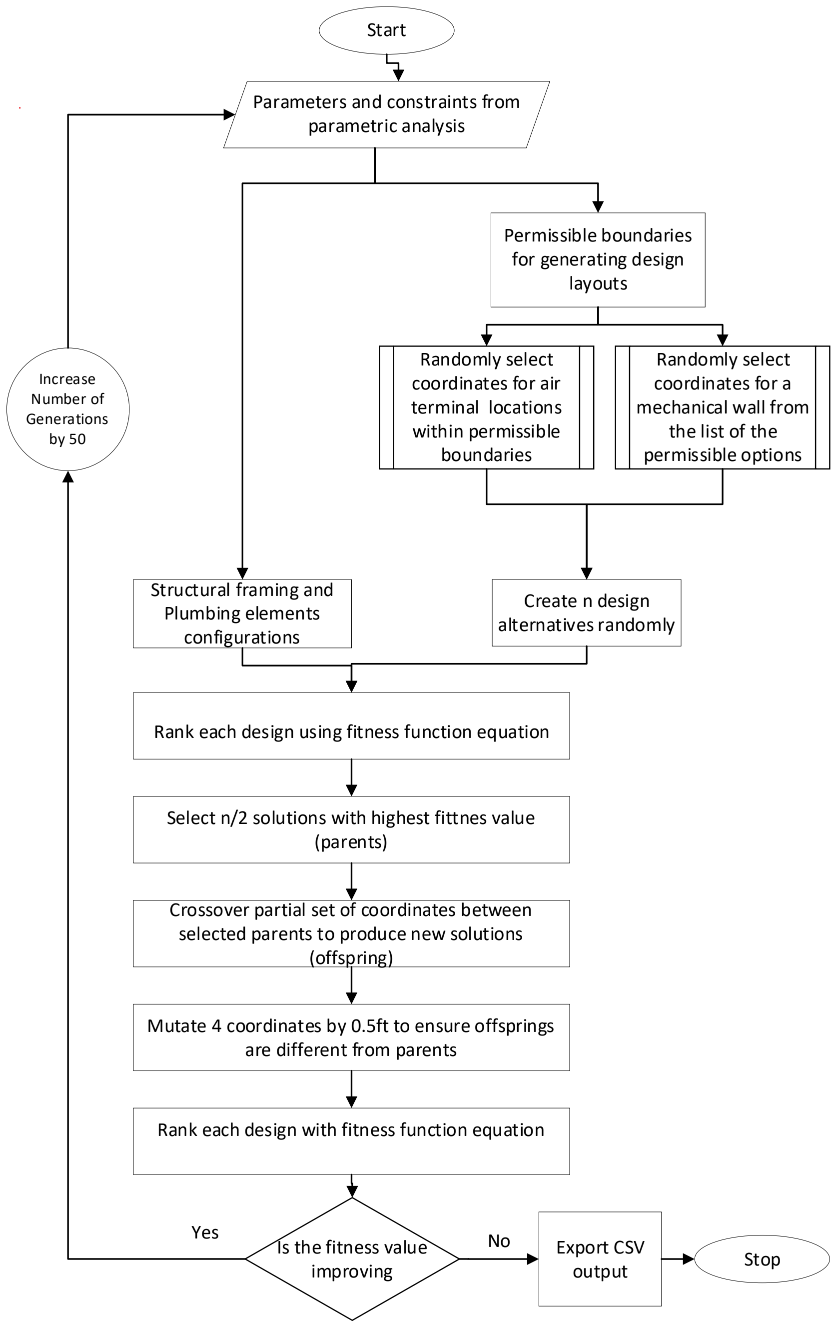


Fig. 37: Process flow for the proposed design optimization of the air distribution system layout with utilizing genetic algorithm technique

Input data -The Input data consists of the constraints imposed during the design process, which can be categorized into two main groups, those having a direct influence over either the system performance or system constructability. The hard constraints need to be identified and considered before calculating the design. The room boundaries, the physical building structure, and MEP systems are identified in the previous parametric analysis, and the geometry of each element is defined as x,y,z coordinates. These parameters must exist in a 3D BIM model in order to feed accurate information to the algorithm for optimization. The previous chapter reviews the identification of the spatial constraints in the BIM environment. The input files include:

i. Range of possible locations for the air terminals
ii. Different walls that are suitable for installing the vertical duct segments
iii. The floor level is chosen for analysis with the architectural layout
iv. Structural system configuration
v. Plumbing system configuration
vi. Location of the openings (e.g., doors windows, stairs)

Layout generation - The proposed optimization algorithm is programmed to randomly produce a population of design alternatives by selecting a position for each air terminal and a mechanical wall for the given floor level. Each solution within the population has a set of coordinates in accordance with the 3D model input for the selected air terminals. Each set of coordinates is used to create an alternative design layout solution, which is known as an individual. The coordinates within each individual are used to compute the shortest possible path for connecting the terminals. The air terminals are connected via branch ducts to the main duct using a generic tree branch network model as a baseline and then further improved (Equations 4 and 5 are used for calculating the length, respectively). The fitness function evaluates each individual based on the total calculated length and the number of intersections that the duct route will have with existing building elements. The fitness function acts as a penalty function; therefore, it assigned a negative value to each measurable objective. The solution with the highest fitness value is the fittest individual. The best individuals are selected as parents to produce the next generation of individuals. The next generation must further improve the fitness of the solution. The Fitness function is presented in the fitness function section. The process includes the following steps:

i. Assign a location for each air terminals in all spaces
ii. Select a mechanical wall
iii. Find the length of the main duct branch (equation 4)
iv. Find the length of all the branch ducts connecting to air terminals and the mechanical wall (equation 5)
v. Calculated total length
vi. Calculate the number of intersections with the structural system
vii. Calculate the number of intersections with the plumbing system
viii. Rank each solution and create a list using the fitness function (equation 4)

Improving and evolution - A one-point crossover takes place between the selected fittest individuals, known as parents. In this framework, crossover occurs by switching the odd genes and the even genes between every two consecutive parents, starting from the number 1 selected individual. The reason being is that the individuals consist of X_n and Y_n according to the number of existing air terminals in the project, and the crossover needs to be done accordingly to ensure that the new individuals consist of half of the genes from each respective parent. With the correct exchange of genes, the new location for the air terminals will exist within the permissible boundaries, and the solution remains acceptable.

The process of mutation is done by randomly selecting a number of genes and changing them with a low rate of -0.5 to 0.5 to ensure that the resulting coordinates will be within the permissible boundaries. The permissible boundaries are identified in the parametric analysis and defined as an acceptable region for the installation of the air terminals. If the new coordinates fall outside of the calculated boundaries, they are not accepted, and the genes will repeat the mutation until the values are acceptable. The process of mutation and cross over is done to introduce new solutions in the iteration process. The two steps for improving and creating new solutions are:

i. Cross over genes between every two consecutive parents
ii. Mutate random genes to ensure the offspring are different from parents

Iteration process – After feasible changes are applied in the evolution process, a new set of solutions is generated. Accordingly, each solution is rated based on its fitness value by assessing the total length and the total conflicts that exist in the solution. The goal is to generate solutions that result in higher fitness values. The process is repeated by creating a new list starting with the fittest individuals and choosing parents and generating new solutions until the solutions do not improve anymore and reach a limit. The optimum number of generations, mutation rate, total population, and the number of parents is discussed in this chapter for achieving the optimum solution with optimal processing time. The iteration process is as follows.

i. Generate a new population-based on the evolutionary alterations
ii. Repeat the process from generating layout solutions until the results do not improve anymore and reach a limit.

Solution – The final generation will produce a list of solutions that have achieved the highest fitness value in the entire process. The number one solution in the list will be identified as the optimum solution. This solution will consist of the least total duct length and number of conflicts between the design ductwork layout and the structural system and the other existing MEP elements. This solution is exported in a CSV file that contains the required coordinates for the location of the air terminals and the duct network layout configuration. The output is later used for generating the air distribution system in the BIM environment. The summary of the output:

i. Set of coordinates representing the location of the air terminals
ii. Coordinates for the mechanical wall
iii. Minimum conflicts with the structural system
iv. Minimum conflicts with the plumbing system

Generation vs. improvement

The GA starts with generating random solutions and improves the results over each generation. Figure 38 demonstrates the performance of 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. Figure 38 demonstrates the improvement of the solution of over 100 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. This test was conducted on a simple layout, and the optimum results were achieved after 50 generations. In order to review the optimum number of generation and other GA parameters needed to achieve the optimal results, the following section will demonstrate the recommended parameters.

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

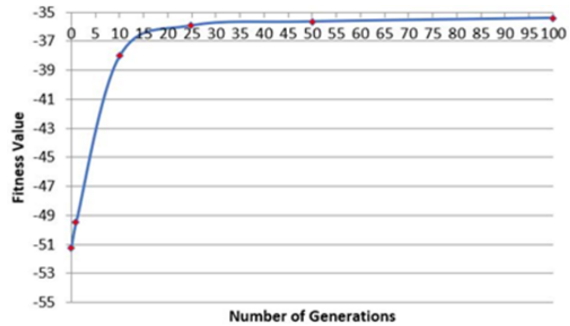


Fig. 38: Improvement of the designed layout over the iteration process (fitness value vs. generation)

Genetic algorithm parameters

The results obtained from the implemented GA optimization display a variation and dependency based on the following parameters: number of parents, population size, and the number of mutations in each generation. This section demonstrates the behavior of the proposed algorithm with respect to the user input and variation of the GA parameters. GA is developed based on random selection and improvement; therefore, each time the algorithm is executed, it will result in a slightly different solution. The following Figure 39 is an example of an individual solution generated by the algorithm with respect to the permissible boundaries for each air terminal coordinates and the mechanical wall location, and each solution will be assessed using the fitness function. In this case, 6 spaces are requiring one air terminal each, and one mechanical wall is required, resulting in 7 x-values and 7 y-values per individual.

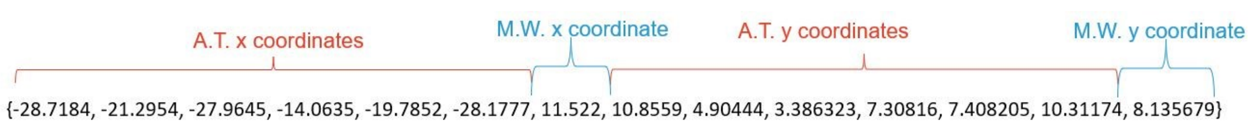


Fig. 39: Individual solution with randomly produced genes

To clearly demonstrates the behavior of the evolutionary process, the following graphical analysis (Figure 40) on the case study represents the change, and the variation that occurs as the number of mutations increased from 1 to 14 to account for the 14 coordinates that exist in each solution. If the mutation rate is 14, all of the resultant variables will change, and the result can deviate from improvement; therefore, the optimal rate of mutation must be identified. Increasing the mutation rate too high will eliminate the effect of the crossover, which aims to produce offsprings based on the genes from the selected fittest parents. To further analyze the sensitivity of the data, the following Figure 40 presents the fitness evaluation based on a fixed number of generations, 100, vs. an increasing number of mutations (1-14).

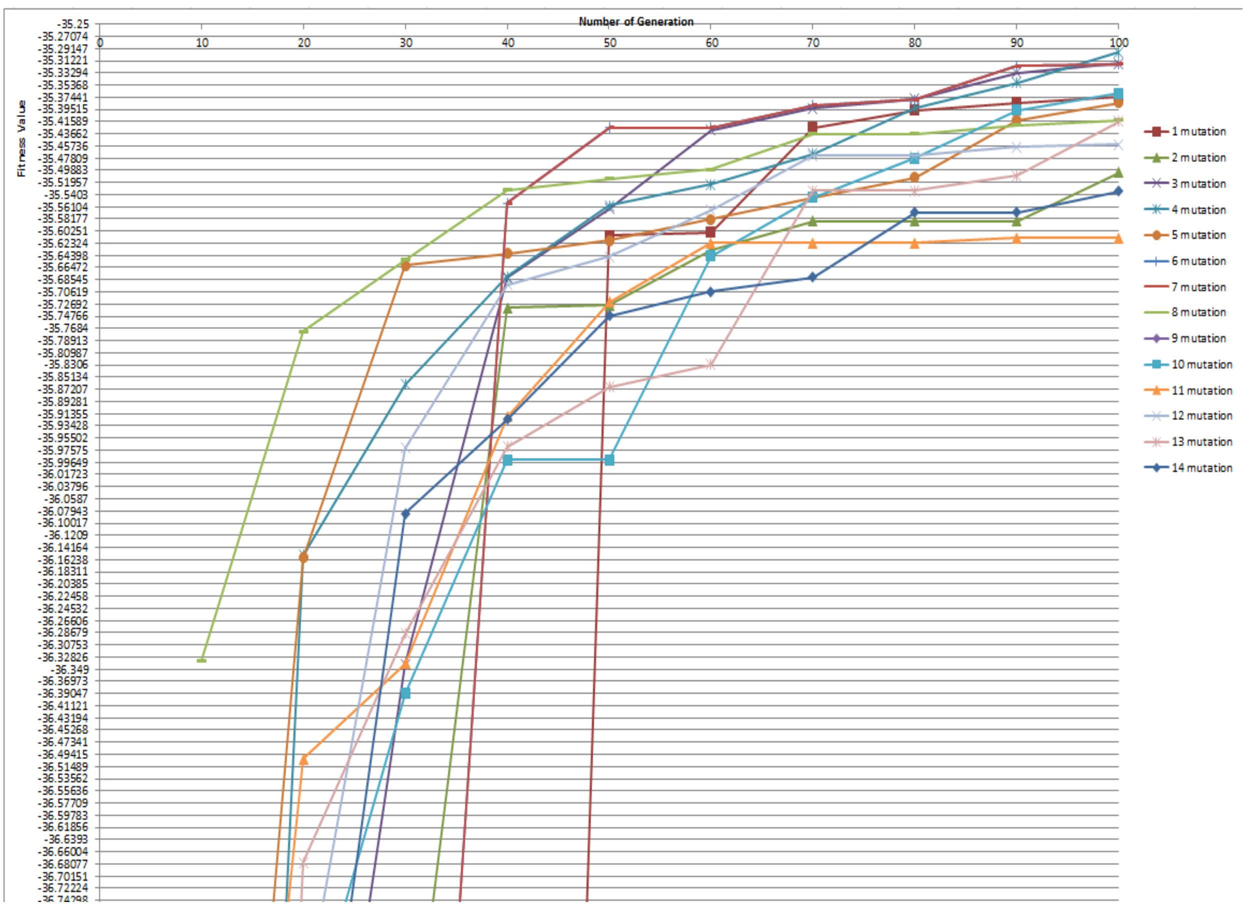


Fig.40: Fitness value vs. 100 generations and mutation (1-14)

Based on the performance of the data in Figure 40, the mutation rate of 4 results in the highest fitness value -35.29 over 100 generations. It is recommended to keep the mutation rate at 27% of the coordinates (4/14) to maintain producing a reliable increase in the fitness value. The mutation rate of 4 is selected to analyze the sensitivity of the data; further, the following Figure 41 presents the fitness evaluation based on a fixed number of mutations, 4, vs. 100 generations. The result displays a reliable improvement over the evolution process.

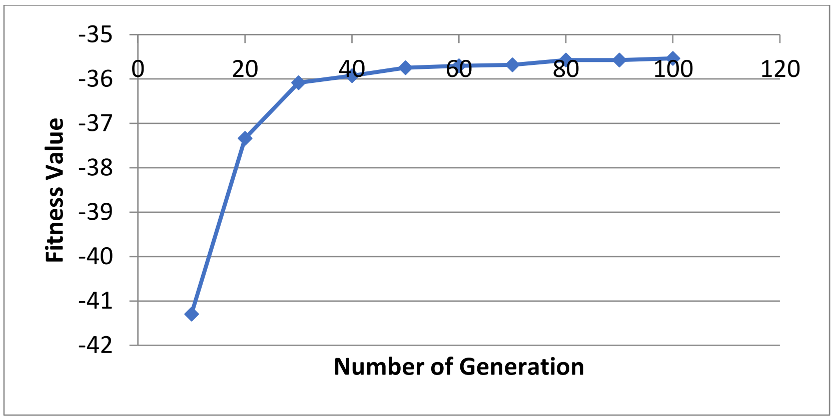


Fig. 41: Fitness value vs. the generation and mutation rate is 4 fixed

3.2.2 Summary of Findings

It is proven that implementing genetic algorithm optimization is beneficial in planning the air distribution layout in accordance with the design and construction requirements. The algorithm can automatically assess different solutions and find the path towards the solutions that satisfy all of the objectives and constraints set in place. As a result, the final solution generated by the algorithm will improve the design by reducing the total length of the ductwork layout, the total number of intersections with the structural members, and total conflicts between the ducts and the existing MEP elements in the project.

The optimal parameters used for implementing the GA algorithm include population:50, parents: 25, generation: 100, and a mutation rate of 27%. Based on the analysis in this chapter, these parameters are recognized to produce reliable results with optimal processing time. The evolution and improvement process reaches a limit after 100 generations depending on the complexity of the project until the solution cannot be improved any farther. In the next chapter, the algorithm is tested in various case studies, and the results provided support the benefits of this application.

Parents and Population

As mentioned above, the ideal relationship for the population size and the number of selected parents is num*_parents*=0.5 x *Pop_Size*. The reason being is the cross over process that takes place between every two consecutive parents; therefore, the resultant offsprings cannot exceed half the population size. If more than half the population is selected as parents, there will be more solutions produced than the total allowable population size. Based on trial and error, it is concluded that the population size of 50 results in the achievement of the highest fitness value with optimal processing time for the given project size.

Parents: 25

Population: 50

Crossover

Every two consecutive parents produce one offspring. Each individual consists of n number of x and y according to the number of air terminals required in the project plus the mechanical wall, and the crossover needs to be done accordingly to ensure that the new individuals consist of half of the genes from each respective parent. With the correct exchange of genes, the new location for the air terminals will exist within the permissible boundaries, and the solution remains acceptable. This means that there will be the same number of offsprings as the number of parents, and the total is equal to the population size. Therefore, the total number of parents must be half the population size. If a less number of parents are assigned, there will be repetitive offspring produced, and it will slow down the process of improvement over evolution. Also, if the number of parents is more than half of the population, the excess offspring individuals will not be registered.

Crossover: must occur between the odd and even genes to ensure the x and y coordinates of each point are exchanged, respectively.

Generation

Based on the behavior of the observed data, it is recommended to use a higher value of generations +50 and a mutation rate of 27% of the total coordinates for the optimal results. The product of different generation and mutation values are displayed in Figure 40 in accordance with the resultant fitness value. More generations may be required for more complex projects until the optimal solution is discovered. The iteration process in the framework recommends increasing the number of generations until the results do not improve any farther and reach an acceptable limit.

Generation: 100

Mutation Rate

For the purpose of creating new generations with offspring that are different from both parents, the mutation function alters randomly selected genes within an identified range of values known as the rate of mutation. This alteration between the parent's genes and the offspring is specified to be within -0.5 and 0.5, which are presented as a fraction of feet imperial units identified in the project model. This small range will limit the deviation of the result and will help to achieve the most optimum result faster over the course of the evolution process.

Mutation: 27% of the coordinates at the rate of -0.5 – 0.5

3.3 3D Visualization and Detailing the Design

This section will present the third procedure in the proposed methodology, which is 3D visualization and detailing. The concept of automatically producing design solutions is referred to as generative design. While the generative design may sound futuristic, it is already changing how decisions are made during all phases of the design and construction process. With generative design, specific design parameters are defined to generate optimal solutions. With the user's guide, the solution will arrive at the optimal design along with supportive data to prove which design performs best. In this section, the result of the previous optimization algorithm is imported back into Autodesk Revit and transformed into a 3D model. The following procedures take advantage of the BIM data to create quantity takeoffs and complete a cost analysis to validate the benefits of the proposed designs. Other simulations and design validation tools are discussed for farther analysis of the HVAC system. Based on the literature review, there are automated features available in BIM to assist the HVAC engineers in developing their design. The features used in this study include the heating/cooling load calculation, duct sizing, pressure loss reports, clash detection, and quantity takeoff calculations based on the project model in Autodesk Revit. The flow chart below (Figure 42) demonstrates the order of applying the BIM design features with respect to the proposed methodology for the development of finalizing the designed air distribution system layout.

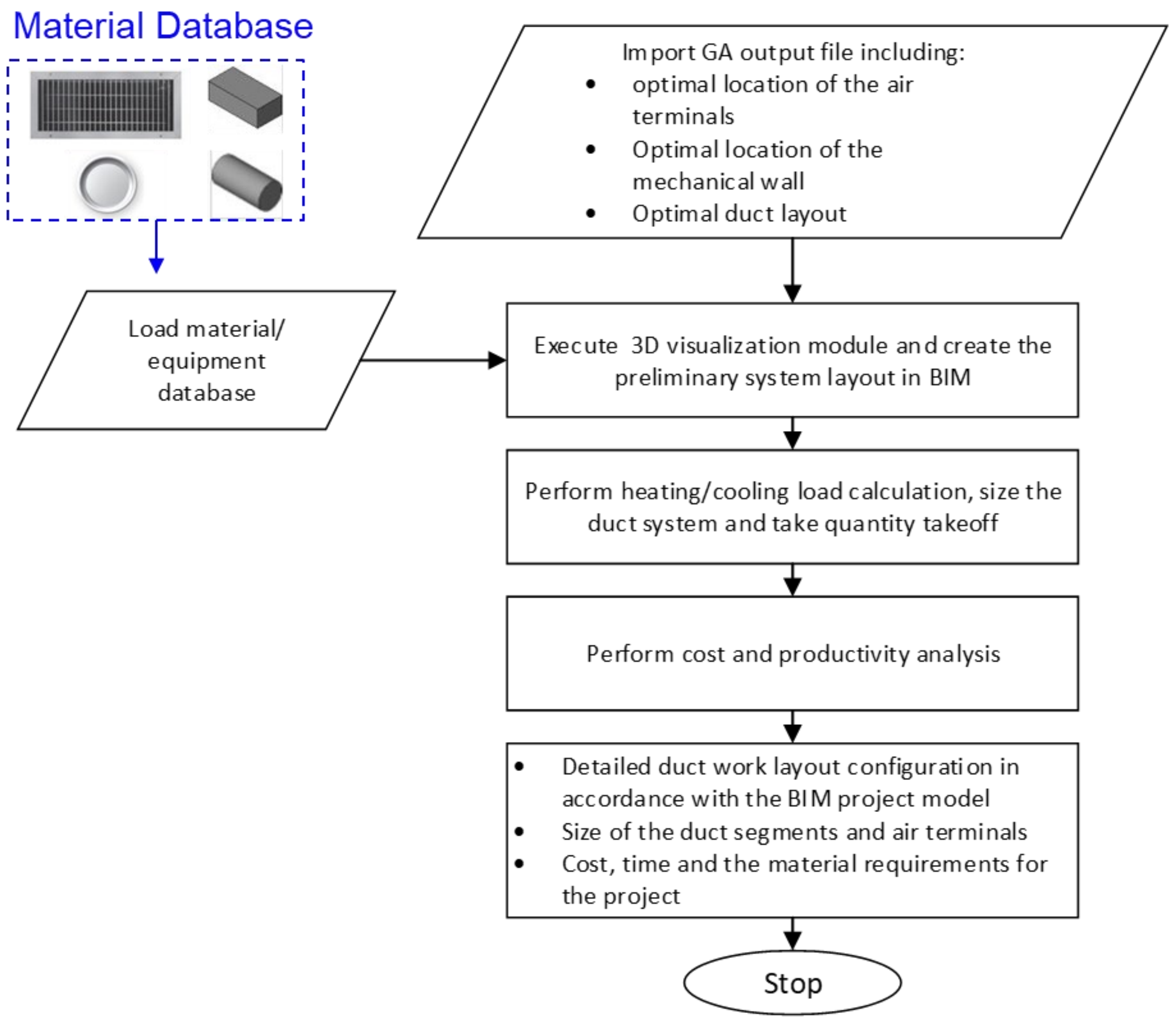


Fig. 42: Process flow for the 3D visualization and detailing of the air distribution system layout

The input required for the creation of the air distribution system in 3D environment are:

i. The result of the GA optimization (.CSV)

ii. The 3D air terminal and duct families in Revit

3D Visualization and detailing:

i. Execute dynamo module to create 3D model (Figure 43)

ii. Perform heating/cooling load calculations

iii. Perform the sizing of the ducts using an equal friction method with a high velocity of 2000 fpm.

iv. Extract quantity take off

v. Perform productivity and cost analysis

Output and the results:

i. Detailed ductwork layout configuration in accordance with the BIM project model

ii. Size of the duct segments and air terminals

iii. Cost, time and the material requirements for the project

This section will demonstrate the process of 3D visualization and detailing.

3D visualization

The result of the optimization algorithm is a series of points that define the optimal location of the air terminals and the mechanical walls. The results are exported in CSV format, and the final Dynamo module is in charge of processing this data and generating the 3D model accordingly. Figure 43 below is the Dynamo module programmed to mathematically calculated the ductwork layout configuration using the input coordinates and create the 3D model.

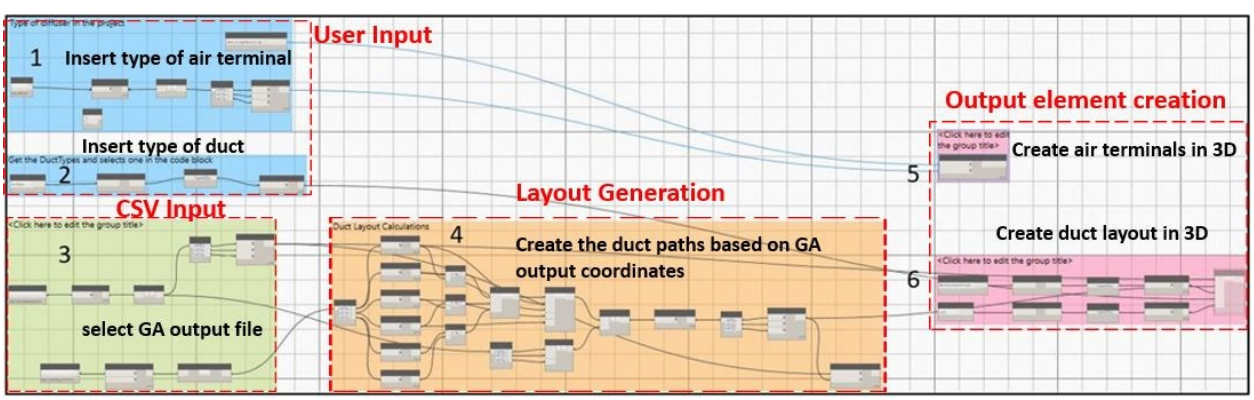


Fig. 43: Dynamo algorithm for generating the 3D model

User input: Block number 1 and 2 are the user inputs. Block 1 is the type of air terminal that the user chooses based on the functionality, appearance, and material specifications. The user may choose an existing floor-mounted register, or ceiling diffuser from the Revit database, or create one that represents the products offered by their company. Block 2 is the type of duct material and shape that will be decided by the user. At this stage, the size of the duct system is not determined, and only the options are a rectangular or circular cross-section from the family database in Revit. The duct material can be specified in the project properties.

CSV input (GA output): Blocks 3 is the input file that includes the location of the air terminals and the mechanical wall. This file is the output from the GA optimization and includes the air distribution layout coordinates.

Layout Generation: Blocks 4 contains a series of customized nodes programmed to compute the configuration of the ductwork layout. The calculations in this block are demonstrated in chapter 3, section 3.1.3 (creating the air distribution layout), where the length of the main duct and the branch ducts are calculated. In simple words, the main duct will be centered in the middle and connects to all the air terminals and the mechanical wall via a series of branch ducts with 90-degree connections. These input coordinates are categorized as start and endpoints to facilitate the drawing of the ductwork in the 3D model.

Output and element creation: Block 5 and 6 are the outputs of this module. They are in charge of creating the elements in the 3D model. Block 6 places the air terminals, and block 7 will generate the ductwork layout for the specified floor level.

Heating/cooling loads

Parametric modeling in BIM enables the designers to include the required thermal properties of each building element in their design. If BIM is implemented for a project, designers have access to the walls, floors, ceilings, doors, and windows thermal resistances. There is an automated function for the calculation of the heating/cooling loads embedded within the Autodesk Revit. This information is necessary for choosing the correct supply of diffuser's sizes and capacities to meet the maximum load intensity of each room. For example, a room that requires 100 CFM can have one diffuser that can meet this flow rate or two diffusers with 50 CFM depending on the availability and the type of the air terminals defined by the user. The designed ducts must be able to sufficiently carry the required flow rate based on the load calculation.

Sizing ductwork system

The duct sizes are determined by specifying the design methods. The available sizing methods in the Autodesk Revit include equal friction and static regain with specified friction and velocity. Each air terminal will be assigned the required flow rate after the heating and cooling loads are calculated. Accordingly, the branch ducts that are connected to each air terminal will be assigned the required size to support the assigned flow rates. The air distribution system consists of many branch ducts and main ducts that are in charge of delivering the flow of air and returning it to the central air handling unit. When the total available pressure for the system is known, applying this method will measure the loss of pressure per unit of length based on the longest duct line and ensure that the same pressure loss per unit of length is applied although the system. The equal friction method will ensure that the pressure loss in the duct channels is adequate, and the velocity of 2000 FPM should be assigned to achieve a high-velocity system based on the client requirements. There are three equations that can be used for sizing the duct based on the velocity and specified friction inputs, including Altshul-Tsal equation, Colebrook equation, and Haaland equation, and the user can choose the preferred method. The nominal duct sizes can be identified based on the user's input, and the system will automatically adjust the duct sizes to meet the user and the design requirements.

Pressure loss report

Pressure loss is important to the design engineers to ensure that the duct segments are designed effectively to handle the pressure caused by the flow inside the channels. If the pressure loss is not adequate, it can cause problems such as vibration, noise, and insufficient flow in different parts. Shorter ducts will require dampers to resist the extra flow and vibrations. Revit is capable of generating pressure loss reports based on the designed air distribution system in the BIM environment.

Clash detection

The interference amongst different project elements such as the duct, the pipes, and the beams can be automatically detected using a built-in interference detection feature in Revit, also referred to as the clash detection tool. The level of tolerance can be adjusted based on user preference. It is recommended to use 1 inch as the tolerance for the interference and clash detection, meaning if the elements intersect with more than 1 inch, then they will be required to be adjusted to solve the conflict. The conflict resolution is often completed manually; however, different automated tools for handling system clashes are reviewed in the literature study section of this thesis. The clash detection tools will be used to validate the result of the design optimization algorithm, which aims to minimize the design conflicts.

Quantity takeoff, cost, and productivity analysis

After the duct, sizes are calculated, and clash detection is performed, the detailing procedure is complete, and the 3D model is ready. Quantity takeoff is the main procedure for calculating the total material required for the construction of the project. One of the most useful features of Revit is that all the materials can be automatically categorized, and the quantities can be quickly estimated. The total material quantity is essential for estimating the cost and duration of a project. In this research, the quantity takeoff feature of Revit is used to assess different design solution in terms of total project cost and duration. With access to BIM, there is a high degree of certainty on how much duct is required to be fabricated. The quantity takeoff can be done by utilizing the BIM model and exporting the ductwork schedule. The total area of the sheet metal is calculated using the cross-sectional area of the ducts segment and the associated lengths. The total weight of sheet metal required for fabricating the ductwork system is calculated using standard galvanized steel gauge sizes.

RSMeans Building Construction Database

This section demonstrates how the RSMeans database can be effectively used to quantify the total cost and time associated with the fabrication and installation of the designed ductwork layout [27]. The following data is retrieved from the RSMeans online database. The construction data for galvanized steel ducts are provided in section 23.31.13.13.05 (Figure 44), and the required crew formations are given (Figure 45). Accordingly, the associated cost and total construction time can be calculated based on the available historical database. Figure 44 below demonstrates the Master Format used to locate this data.

RSMeans online	
23	HVAC
23.31	HVAC ducts and Casting
23.31.13	Metal ducts
23.31.13.13	Rectangular metal ducts
23.31.13.13.05	Galvanized steel
* 23.31.13.13.05.20	100lb-500lb
** 23.31.13.13.05.40	500lb-1000lb

Fig. 44: RSMeans database utilized for HVAC unit cost estimation (Master Format) [27]

*Metal Ductwork, fabricated rectangular, galvanized steel, 200 to 500lb., includes fittings, joists, supports and allowance for flexible connection, excludes insulation

**Metal Ductwork, fabricated rectangular, galvanized steel, 500 to 1000lb., includes fittings, joists, supports, and allowance for flexible connection, excludes insulation

Crew Q-10	Hr.	Daily	Hr.	Daily	Bare Costs	Incl. O&P
2 Sheet Metal Workers	$57.25	$916.00	$87.50	$1400.00	$53.43	$81.67
1 Sheet Metal Apprentice	45.80	366.40	70.00	560.00		
24 L.H., Daily Totals		$1282.40		$1960.00	$53.43	$81.67

Fig. 45: Workers crew formation for installing the ductwork [27]

RSMeans uses the total weight of the ductwork in pounds required for estimation of the time and cost of the projects. The total time of construction in the factory environment is different from the traditional site-construction. In off-site construction, the workers install the ductwork inside the floor panels and the wall panels on the specific workstation, which does not require over the head installation. RSMeans assumes a height of installation of less than 10’ for the productivity analysis, and additional installation height would add a percentage to the cost and time calculations. Therefore, it is adequate to use RSMeans for estimation of the total cost and time associated with the construction of the ductwork for off-site construction in this research. The predicted results and potential benefits of this methodology are demonstrated in the following chapter, which is the implementation and case study.

Chapter 4: Implementation and Results

4.1 Introduction

This chapter will demonstrate the implementation of the proposed methodology on the case study where HVAC construction was identified to be overly time-consuming. In the case study, the manufacturer applies panelized construction as the primary method for delivering each project; thus, HVAC systems for prefabricated buildings are installed on the manufacturing line. Offsite construction is in growing demand due to its ability to save time and cost, to provide a safer work environment, and to reduce waste. Panelized construction has been adopted increasingly across Canada because it is simple and effective, especially with wood and light-gauge steel framing.

In this academic work, a generic research methodology is proposed for optimizing the design and development of HVAC projects in the prefabricated home building production process. This work is demonstrated through industrial applications based on multiple case studies provided by industrial collaborative partner ACQBUILT Inc.—a major production homebuilder based in Edmonton, Alberta. ACQBUILT has established North America's leading state-of-the-art home building facility. The company uses wood-framed, panelized construction for various buildings, including attached-garage, detached-garage, duplexes, townhouses, and condos. For each project, the majority of construction tasks are completed in the facility. Open wall panels, floor panels, and roof panels are prefabricated offsite and delivered to the site for rapid assembly. ACQBUILT has recently started to install building services, including electrical, plumbing, and ductwork elements, in the offsite environment as well. Previously, subcontractors were left to install each building service system after the onsite structure of the building was complete. Installing building services in an offsite environment allows the company to deliver their projects faster, reduce the cost of the subcontractors, and eliminate the waste that is produced on the construction site.

Installing MEP systems is a significant part of each building project that influences not only the quality but the duration and cost of a project. The purpose of offsite construction is to enforce fast-paced construction, which requires a high degree of coordination and collaboration between trades. Meanwhile, the company identified that the installation of the duct system varied significantly between each project in terms of time and cost associated with the completion. In line with the requirements of ACQBUILT, the following objectives are proposed:

(i) The designed air distribution system must be easy to install in the offsite environment to reduce site work as much as possible.

(ii) The system must be energy-efficient and incorporate a high-performance air distribution.

As a part of ACQBUILT's continuing efforts to improve its construction process, this research uses BIM and optimization techniques to improve the design of the HVAC system and satisfy the requirements of offsite construction. Further, this research may increase productivity on the assembly line and decrease project cost and material waste. This chapter presents the current designed HVAC systems with the associated challenges and problems identified. The results will be compared with the original baseline models to demonstrate the potential benefits.

4.2 Overview of the current projects

ACQBUILT has provided four different project models that are used as case studies in this research. This section reviews the current air distribution systems that are manufactured on wood-framed, prefabricated floor panels, along with the challenges associated with these systems. Each project sample includes architectural, structural, and MEP models provided by the industrial collaborator. Initially, the projects are designed in AutoCAD, which is the traditional drafting tool for 2-D design details. 2-D drawings are effective for communicating design details; however, they are not ideal for a multi-trade, collaborative design process. Traditionally, the coordination of MEP systems with the structural design is completed by overlapping the designs to identify conflicts and analyze congested areas where different systems overlap. For example, if the pipes are overlapping with the duct system, the total thickness of the two may exceed the floor thickness, which will result in a construction conflict. This process is workable but not efficient, because overlapping design details can be difficult to analyze manually, and the depth of the different elements is not considered. An example of a coordinated 2-D design is presented below (Figure 46).

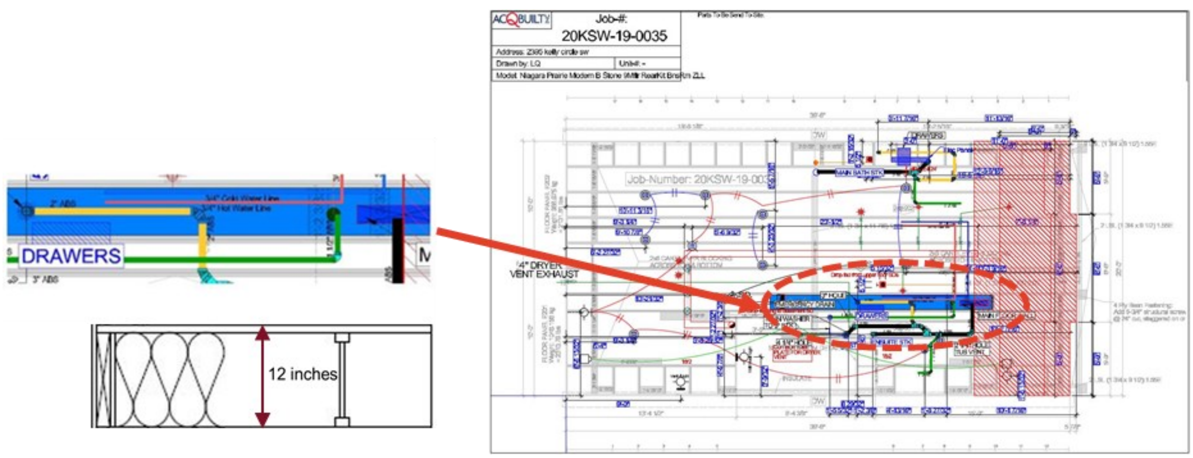


Fig. 46: Prefabricated floor panel with MEP systems overlapping (courtesy of ACQBUILT, Inc.)

Engineers are responsible for designing each system and combining the designs to see the full picture. With using this process, design conflicts and congested areas are not identified until the final designs are compared. The engineers are then required to solve the conflicts and update their designs accordingly, which requires rework. A more effective approach for multidisciplinary collaboration is BIM. Based on the literature review, BIM is an effective tool for coordinating designs during the development of a project model. This will ensure that the discrepancies are solved along the way, so the final designs are coordinated. With access to a full 3D database, the design conflicts can automatically be detected by the system, which streamlines the process of design and eliminates the need for reworking the models. The designers can ensure that all elements fit inside the floor panels because they will be able to view the full picture and compare the depth of different overlapping elements (Figure 47).

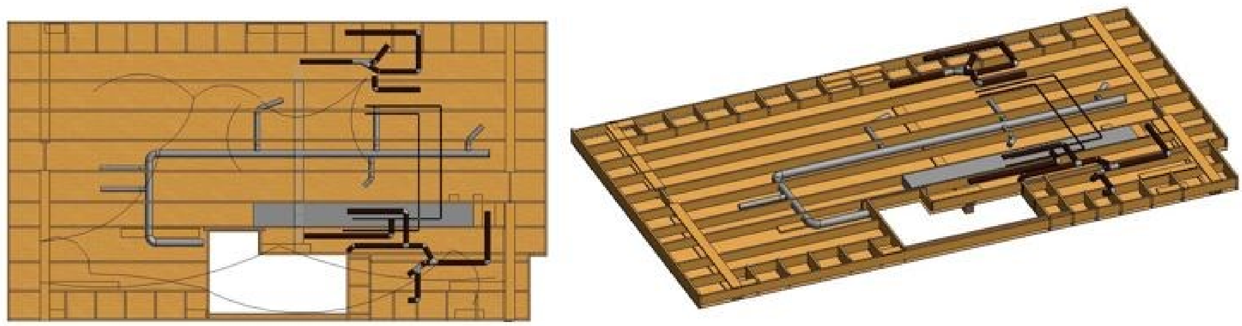


Fig. 47: 3D prefabricated floor panels with MEP systems generated in Revit

In order to access all the project data and analyze the relationship between different elements, a 3D model must be established using a BIM tool. The modeling tool used in this study is Autodesk Revit. Here, floor panels are designed following the structural details provided by ACQBUILT. Utilizing BIM for project development provides access to a variety of tools designed to automate the processes of clash detection, quantity takeoff, heating/cooling load calculation, and duct sizing. Each of these tools is used to assist in developing a full HVAC model in the BIM environment. The elevation of each of the building systems is accurately defined in the 3D model, enabling designers to integrate their models in the same platform. Clashes are automatically identified and demonstrated. (Figure 48)

	A	B
1	Ducts : Round Duct : Taps : id 361796	Structural Framing : Dimensional_Lumber_Plate : TJI 11" : id 361877
2	Ducts : Round Duct : Taps : id 361796	Structural Framing : Dimensional_Lumber_Plate : TJI 11" : id 361879
3	Ducts : Round Duct : Taps : id 361802	Structural Framing : Dimensional_Lumber_Plate : TJI 11" : id 361861
4	Ducts : Round Duct : Taps : id 361802	Structural Framing : Dimensional_Lumber_Plate : TJI 11" : id 361871
5	Ducts : Round Duct : Taps : id 361802	Structural Framing : Dimensional_Lumber_Plate : TJI 11" : id 361875
6	Ducts : Round Duct : Taps : id 361810	Structural Framing : Dimensional_Lumber_Plate : TJI 11" : id 361877
7	Ducts : Round Duct : Taps : id 361812	Structural Framing : Dimensional_Lumber_Plate : TJI 11" : id 361877
8	Ducts : Round Duct : Taps : id 361818	Structural Framing : Dimensional_Lumber_Plate : TJI 11" : id 361875

Fig. 48: Interference check between ductwork and the I-joists (Revit)

Multiple clash detections were detected on the sample projects, suggesting that the current design contains excessive interference between the ductwork and the structural beam system. In the construction plans, for every location that the ductwork intersects with a beam, a hole must be cut out of the beam to route the duct through (Figure 49).

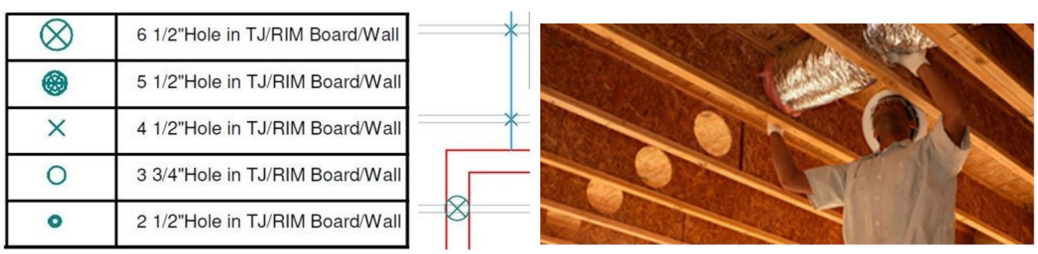


Fig. 49: a) predefined location for drilling holes in the joists (courtesy of ACQBUILT, Inc.) and b) construction process of routing the ducts [68]

Cutting holes in the structural beams requires more construction time. It creates more construction waste and may damage the structural integrity of the framing system. In the case studies, the beam system is designed using I-Joists. I-joists are proven to be cost-effective and flexible in terms of their lengths; however, they are more difficult for running the mechanical and plumbing systems through. The OSB paneling is restricted to a number of small holes in predefined locations, and additional holes must follow strict guidelines to ensure that structural integrity is not compromised.

The total number of holes is dependent on the original design of the air distribution system layout. A small modification can be made manually to fit the designed ductwork layout inside the floor framing system. However, with the designs used by ACQBUILT, the total number of the holes required is too high, and the proposed methodology aims to reduce the number of holes required in the beams. With less conflict between the ductwork and the structural framing system, the installation process will be made similar, and the workers can install duct segments more rapidly without the need for drilling holes and securing ducts inside of beams.

Another coordination challenge exists when the ducts and pipes overlap. The ductwork is installed prior to the installation of the pipes. The pipes are smaller in the cross-section area; therefore, they can fit more easily inside the panels. Although the plumbing system does not intersect directly with the ductwork, there are locations where the two systems overlap. Overlapping of different building systems directly affects the construction processes. Each system requires trade laborers who are experts in installing their specific systems. Therefore, the areas where the two systems overlap require extra time for installation. For example, the plumbing trade workers must wait until the sheet metal workers have fully installed the ductwork before proceeding with the installation of the pipes. This creates idle time for the worker and increases job duration. In offsite construction, the simultaneous construction of different building elements can significantly shorten the job duration. Congested MEP systems are also harder to access for maintenance, and leakage from one system can negatively affect the adjacent one. Visual investigation of the different project samples was performed, and a significant amount of MEP congestion and overlaps were identified (Figure 46).

Air distribution system design

The current heating system used in the case study projects is a ducted furnace for high-velocity heating and a heat recovery ventilator HRV for ventilation purposes. This is a common system combination in houses built in cold climates. The HRV system deals with excess moisture during the heating season and provides fresh air to the building enclosure. High-velocity heating systems are designed with smaller duct sizes and higher flow rates to adjust the house temperature at a more rapid rate. Other features offered by this company are a Wi-Fi programmable thermostat and humidifier to promote higher occupant comfort and customer satisfaction. The case study projects are presented in Figure 50 below, with details on the heating and ventilation systems.

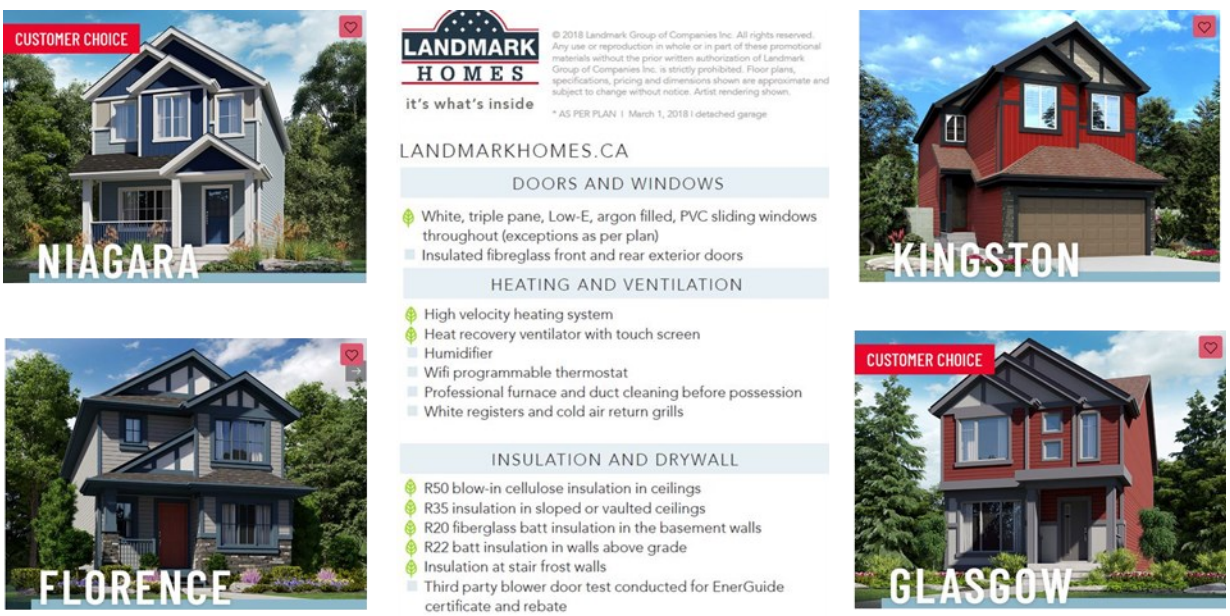


Fig. 50: Prefabricated single-family houses used for the case study(courtesy of ACQBUILT, Inc.) [59]

In the four given projects, the mechanical room is located in the basements (Figure 51). The mechanical room facilitated the installation of the furnace and the HRV system. The ductwork is centralized in this location and connected to the supply outlet and return inlet of the air handling units. The supply duct system is connected to the floor registers in each of the spaces around the building to circulate the heated air (Figure 52 red circles). The return air system is centralized on each floor to capture the used air and return it back to the furnace for mixing fresh air, exhausting, reheating, and recirculation (Figure 52 blue circles).

Fig. 51: Mechanical room in the basement, gas furnace and HRV (courtesy of ACQBUILT, Inc.) [59]

Fig. 52: Floor-mounted supply air registers and return air vents on the walls (courtesy of ACQBUILT, Inc.) [59]

The proposed methodology is applied to the given projects to facilitate the design of a more efficient ductwork layout. The proposed designs will enhance construction productivity, reduce cost, minimize material waste, and contribute significantly to the building prefabrication industry. To this end, the proposed methodology will be implemented in this chapter, starting with parametric analysis in Dynamo to analyze the Revit BIM models; then, then the GA optimization algorithm will be used to design a new, optimized ductwork layout for each project. The final results will be presented in the 3D model to compare with the baseline design provided by ACQBUILT. This process is applied to four different cases to demonstrate consistency and validate the results.

After investigating each project, it was identified that there are challenges that influence installation tasks on the assembly line, thereby increasing labor time during construction. It is concluded that the following problems affect the installation of ductwork in panelized construction of prefabricated floors and walls:

i. The designed ductwork layout is unnecessarily lengthy and includes branch ducts with unfavorable angles. The original designs are challenging and time-consuming to construct and assemble on the manufacturing line.

ii. The designed ductwork layout interferes with structural framing and requires excessive rough-in work. Each time the duct paths intersect with a beam, holes must be cut in the beams for routing the ducts. This task prevents the rapid installation of the ducts and is time-consuming.

iii. The ductwork and plumbing system is designed to be placed in the exact same plenum space. On multiple occasions, the two systems overlap and cause congested junctions. This issue prevents the simultaneous installation of the two trades, thereby inducing idle time for the laborers.

To address these challenges, the proposed methodology seeks to improve HVAC design and constructability in panelized homes. New and improved designs for the air distribution system layout are proposed to optimize the design and constructability parameters. To validate the effectiveness of the proposed methodology, the results are compared with the original design using four multi-level houses with different architectural layouts. In this chapter, I will demonstrate the implementation of the proposed methodology on the different case

The provided data from the company is in 2D CAD format. The first step is designing the models in the 3D Revit modeling software. According to each step in the proposed framework, initially, the parametric analysis must be performed to extract the necessary data from each model project in Revit (section 3.1). The second step following the parametric analysis is the genetic algorithm design optimization, which solves the design challenges and produces the optimal solution (section 3.2). Finally, the result must be transformed back into the 3D model using the developed 3D visualization module. In this stage, the user must define the type of air terminals, duct and the fitting they want to use in the project and the developed dynamo modules will automatically generate the air distribution system in 3D based on the available material, and the design layout configuration and remaining step is detailing the design and preparing cost and time estimation (section 3.3). In this chapter, each of the discussed procedures will be demonstrated in the case study with details of the results.

4.3 Case study

The following case study includes the 3D BIM of the Niagara model project—a 3-story, detached garage, single-family home with an area of 1200 ft^2 (Figure 53). In this project, there are 11 spaces that require supply outlets for heating purposes, and there is a central return air system installed in the walls to meet the ventilation requirements and impose heat recovery. Following the framework presented in this chapter, the first step is to develop a 3D BIM model; this will serve as the primary source of data for parametric analysis and design optimization of the air distribution system layout. A 3D model of the project is established according to the detailed CAD drawing provided but the collaborative company. This developed BIM must consist of accurate material thermal and physical properties to develop a design that fits the project requirements according to the client's needs. The 3D model, including the architectural, structural, and plumbing systems, is developed in Autodesk Revit to facilitate the proposed methodology.

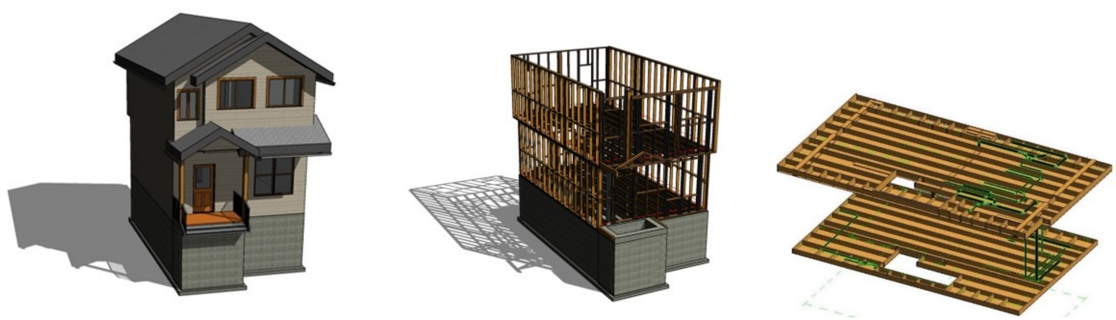
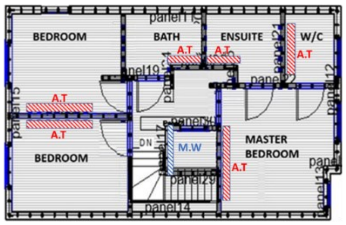


Fig. 53: Niagara project model in Revit (structural floor panels and associated plumbing configuration according to original plans)

This project consists of floor-mounted supply registers that deliver heated air to each room. According to the company's air distribution system design, there is a total of 14 supply outlets in this project. There are six floor-mounted supply registers on the second floor of this building, five floor-mounted registers in the main floor area, and three ceiling-mounted supply diffusers in the basement. The first step of the proposed methodology is to complete a parametric analysis of the project. The second floor and the main floor require floor-mounted registers; therefore, the Dynamo module design must be executed to locate the positions for floor-mounted registers on these two floors (Figure 54). The results are presented as a series of points representing candidate locations for the installation of floor-mounted supply registers. The basement requires ceiling-mounted diffusers, which require a different Dynamo module demonstrated in chapter 3.

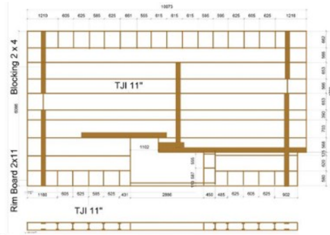
Fig. 54: The Niagara model's room layout and possible locations for floor-mounted supply registers (first floor and second floor)

The output from the parametric analysis module provides a suitable range for the installation of the floor-mounted registers in each room, as well as a selected mechanical wall. Other exported parameters include the location of the structural member and the plumbing elements (Figure 55). These parameters define the constraints and boundaries for the air distribution layout. The range for installation of the floor-mounted supply registers will be used to identify the single optimal location in each room. The mechanical wall is the optimal location for connecting the vertical ducts to the floor below. The structural and plumbing elements will define which routes the ductwork should be installed in order to avoid system interferences and conflicts in the design. Accordingly, there are six spaces on the second-floor layout in this project. Figure 55 demonstrates the exported values from the parametric analysis module executed on the second floor.



Permissible boundaries for the installation of the air terminals

Air Termina	MIN x	MAX x	MIN y	MAX y	z VALUES
1	-33.231	-21.946	5.543	6.943	11.22
2	-33.231	-21.946	4.768	5.768	11.22
3	-18.874	-14.227	10.165	11.165	11.22
4	-15.6	-10.394	9.068	10.068	11.22
5	-3.531	-2.531	9.296	13.962	11.22
6	-10.791	-9.791	2.947	7.533	11.22
Mech.Wall	-17.193	-16.693	3.165	7.483	11.22



Structural Members

Structural	min y	min z	max x	max y	max z
-33.991	-3.919	10.975	0.753	-3.794	11.6
-33.991	16.05	10.975	1.883	16.175	11.6
0.878	0.425	10.975	1.883	0.55	11.6
-34.116	-3.919	10.975	-33.991	16.175	11.6
1.883	0.425	10.975	2.008	16.175	11.6
0.753	-3.919	10.975	0.878	0.55	11.6
-20.833	-3.548	10.975	-9.81	-3.423	11.6
-20.827	-3.794	10.975	-20.702	2.366	11.6
-17.212	0.525	10.975	-17.087	2.291	11.6
-33.991	4.597	10.975	1.883	4.722	11.6
-33.991	-1.971	10.975	-20.827	-1.846	11.6
-9.746	-2.016	10.975	0.753	-1.891	11.6
-33.991	-0.047	10.975	-20.827	0.078	11.6
-9.746	0.018	10.975	0.753	0.143	11.6
-33.991	2.291	10.975	-20.958	2.416	11.6
-20.958	2.291	10.975	1.883	2.416	11.6
-33.991	5.877	10.975	1.883	6.002	11.6
-33.991	8.018	10.975	1.883	8.143	11.6
-33.991	9.877	10.975	1.883	10.002	11.6
-33.991	12.018	10.975	1.883	12.143	11.6
			1.883	13.871	11.6

Plumbing Elements

Plumbing	min y	min z	max x	max y	max z
-1.97	3.267	-0.004	-1.619	3.61	11.079
-15.331	12.747	-0.802	-14.987	13.091	11.079
-4.805	10.02	-0.087	-4.628	10.197	11.162
-7.753	10.02	11.183	-4.826	10.197	11.36
-7.952	10.218	11.183	-7.775	11.909	11.36
-7.797	-2.562	11.183	-7.62	-1.042	11.36
-8.154	-1.274	11.183	-7.797	-0.917	11.36
-7.62	-0.739	11.183	-7.196	-0.316	11.36
-8.365	-2.759	11.183	-7.818	-2.582	11.36
-3.42	3.313	-0.087	-3.243	3.49	11.441
-11.501	14.51	11.1	-3.951	14.854	11.444
-3.93	12.151	11.1	-3.586	14.489	11.444
-7.233	11.787	11.1	-3.951	12.131	11.444
-14.966	12.747	11.1	-9.59	13.091	11.444
-7.231	12.854	11.1	-6.115	13.97	11.444
-8.307	12.747	11.1	-7.246	13.091	11.444
-11.566	2.282	11.1	-7.822	2.626	11.444
			-7.457	2.262	11.444

Fig. 55: CSV output from the parametric analysis (permissible boundaries for installation of the air terminals and mechanical walls, structural framing configuration, and plumbing system configuration)

The exported data is in CSV format. The files containing the spatial boundaries of the specified elements will be used to identify the constraints and parameters used in the design optimization algorithm. The selected level 2 determines the elevation of the designed layout; therefore, the x and y values will be used to calculate the ductwork layout and the conflicts between it and the existing structural and plumbing elements. The Python-based GA algorithm is programmed to: read the input files and perform the required calculations to generate the design layout; calculate the total length, and identify the total number of clashes between the layout and the structural and plumbing elements.

The first file contains a range of x and y coordinates used to generate the location for the floor-mounted supply registers in each space. The first design is generated randomly; the coordinates will fall between the identified minimum and maximum values within the permissible boundaries.

The second file contains the location of the doors in this floor layout, which will ensure that any of the selected air terminals do not fall in front of the doors. Once the locations of the air terminals are selected, the calculation for the layout begins. The farther points will determine the start and endpoint of the main duct, which will be centralized according to all the air terminals' positions. When the main duct configuration is calculated, each of the air terminal positions will be connected to the main duct via branch ducts. The mechanical wall will be connected to the main duct in a similar fashion.

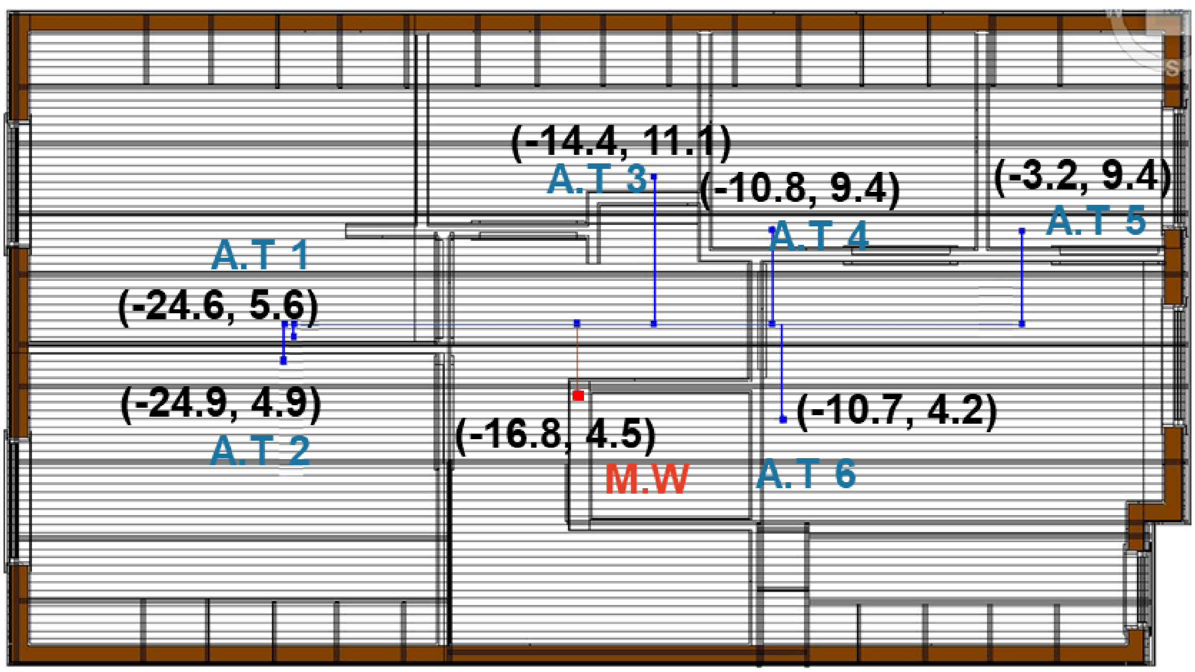
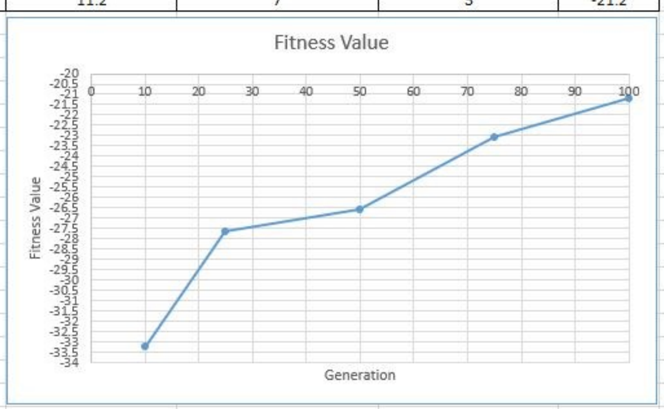


Fig. 56: Second-floor layout and air distribution system configuration (output of the design optimization)

Figure 56 above demonstrates the mathematically formulated layout configuration. The position of the outlets is marked as a blue point, and the blue lines represent the ductwork connection. The red line is the duct connected to the mechanical wall. This wall is used to embed the vertical ducts connecting the two floors. GA can generate a large number of layout solutions based on the given range of locations for the air terminals in each space, with respect to the permissible boundaries. Once the full layout is formulated, each layout will be assessed using the fitness function formula. The total length of the layout is the first measurable objective. The solution that consists of the layout configuration with the shortest length will receive the highest rank. The second objective is interference with the structural system. Both the ductwork layout and the structural system layout are defined in the equation in terms of maximum and minimum points. Each time the systems intersect, it is counted as a single conflict. Although the pipes may not exist at the exact same elevation as the ductwork layout, the x and y coordinates can be used to calculate system overlaps. The overlap of the pipes and the structural elements is the third objective. The sum of all three objectives is defined as the fitness function. The optimization algorithm will generate numerous design layouts based on user preference and search for an optimal layout. After multiple iterations and improvement of the results, the final layout will consist of the shortest duct length and the minimum conflict between the structural system and the pipes. Figure 57 below demonstrates the performance of the GA optimization algorithm on the air distribution layout of the second floor in the case study.

Generation	Duct Length (m)	Ducts & joists intersection	Ducts and pipes ovelap	FitnessValue
10	14.26	13	6	-33.26
25	13.64	10	4	-27.64
50	13.6	9	4	-26.6
75	13.09	7	3	-23.09
100	11.2	7	3	-21.2



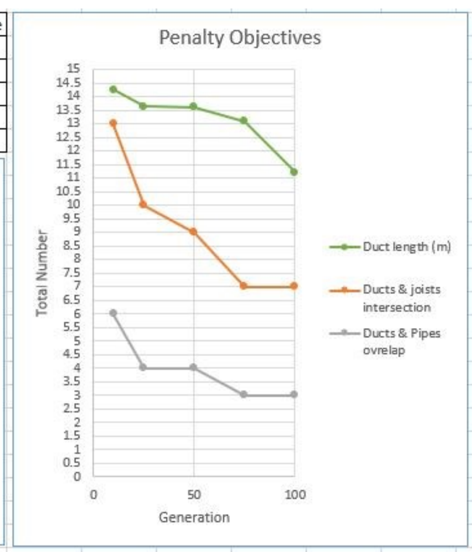


Fig. 57: Optimization algorithm performance on the second-floor layout (Case study one)

At this stage, the design of the supply air distribution layout for the second level is computed. In order to complete the full design, this procedure must be repeated for each level and for the return air system. The basement in this project consists of ceiling-mounted diffusers, which require the specific Dynamo module for the ceiling system to be executed. Each dynamo module is developed to calculate the location for the air terminals according to the design criteria programmed in the module. There are three developed algorithms presented in this thesis: one for designing the floor supply system, one for the ceiling supply system, and the third for the return air system in walls. To make a more practical framework, the steps for the parametric analysis in Revit and for optimization using the GA algorithm are the same for the three systems. The final step is transferring the result of the GA back into the BIM environment for 3D visualization and detailing. The optimization algorithm generates a series of points that define the optimal location of the air terminals and the mechanical walls. The results are exported in CSV format, and the final Dynamo module processes this data and generates the 3D model accordingly. Figure 58 below, is the dynamo module programmed to create the 3D model.

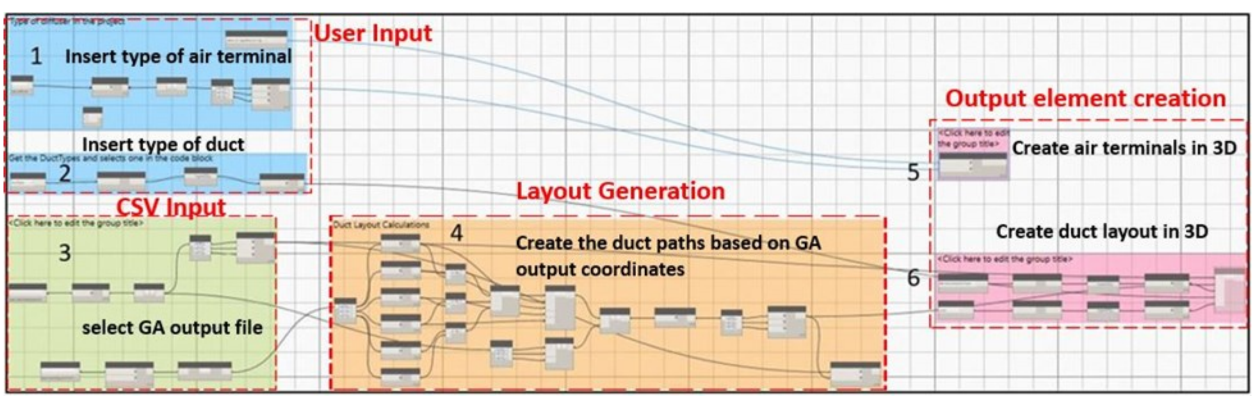


Fig. 58: Dynamo algorithm for creation of air terminals and the ducts in 3D environment

User input: Block number 1 and 2 are the user inputs. Block 1 is the type of air terminal that the user chooses based on the functionality, appearance, and material specifications. The user may choose an existing floor-mounted register, or ceiling diffuser from the Revit database, or create one that represents the products offered by their company. Block 2 is the type of duct material and shape that will be decided by the user. At this stage, the size of the duct system is not determined, and only the options are a rectangular or circular cross-section from the family database in Revit. The duct material can be specified in the project properties.

CSV input (GA output): Blocks 3 is the input file that includes the location of the air terminals and the mechanical wall. This file is the output from the GA optimization and includes the air distribution layout coordinates. The file below (Table 2) represents the 6 air terminal locations and the mechanical wall for the second level of case study 1.

Table 2. Location of the air terminals and the mechanical wall (output from the GA optimization algorithm)

Air Termina	MIN x	MAX x	MIN y	MAX y	z VALUES
1	-33.231	-21.946	5.543	6.943	11.22
2	-33.231	-21.946	4.768	5.768	11.22
3	-18.874	-14.227	10.165	11.165	11.22
4	-15.6	-10.394	9.068	10.068	11.22
5	-3.531	-2.531	9.296	13.962	11.22
6	-10.791	-9.791	2.947	7.533	11.22
Mech.Wall	-17.193	-16.693	3.165	7.483	11.22

Layout Generation: Blocks 4 contains a series of customized nodes programmed to compute the configuration of the ductwork layout. The calculations in this block are demonstrated in chapter 3, section 3.1.3 (creating the air distribution layout), where the length of the main duct and the branch ducts are calculated. In simple words, the main duct will be centered in the middle and connects to all the air terminals and the mechanical wall via a series of branch ducts. These input coordinates are categorized as start and endpoints to facilitate the drawing of the ductwork in the 3D model.

Output and element creation: Block 5 and 6 are the outputs of this module. They are in charge of creating the elements in the 3D model. Block 6 places the air terminals, and block 7 will generate the ductwork layout for the specified floor level.

This process must be repeated for level 1 and the basement in order to complete the ductwork layout calculations and generate the entire air distribution system in the 3D model (Figure 59). The final product will consist of ducts of the same size and floor mounted registers in the appropriate designed locations.

Fig. 59: 3D visualization of the designed system in Revit (preliminary layout)

Detailing the Design

At this stage, the layout is complete, and the next step is to size the system accordingly. The supply outlets must be assigned their specific flow rates. The flow rates are determined based on heating/cooling load calculations. Each air terminal is automatically assigned a specific flow rate—

the rate required to satisfy the calculated loads. Once the supply air terminals have specific flow rates, the ducts are ready to be sized using the equal friction and high-velocity method. These functions require user inputs and will assist in increasing the level of detail in the design. In order to have an accurate result, the input data must include all the details of the building envelope and be confirmed by the engineer in charge. The following Figure 60 presents the load calculations for the master bedroom in level 2, and Figure 61 presents the plan view where the air terminal is assigned the specific flow from the calculated results,

Space Summary - Master Bedroom

Input Data	
Area (SF)	141
Volume (CF)	1,141.98
Wall Area (SF)	202
Roof Area (SF)	150
Door Area (SF)	21
Window Area (SF)	27
Lighting Load (Btu/h)	534
Power Load (Btu/h)	260
Number of People	2
Sensible Heat Gain / Person (W)	73
Latent Heat Gain / Person (W)	45
Infiltration Airflow (ft^3/min)	3.8
Space Type	Bedroom
Calculated Results	
Peak Cooling Total Load (Btu/h)	**4,829**
Peak Cooling Month and Hour	July 8:00 AM
Peak Cooling Sensible Load (Btu/h)	4,763
Peak Cooling Latent Load (Btu/h)	66
Peak Cooling Airflow (ft^3/min)	69.6
Peak Heating Load (Btu/h)	**2,248**
Peak Heating Airflow (ft^3/min)	88.2

Cooling Components	**Total (Btu/h)**	**Percentage**	North (Btu/h)	South (Btu/h)	East (Btu/h)	West (Btu/h)	Northeast (Btu/h)	Southeast (Btu/h)	Northwest (Btu/h)	Southwest (Btu/h)
Wall	-3	-0.06%	0	-54	51	0	0	0	0	0
Window	4,048	83.82%	0	0	4,048	0	0	0	0	0
Door	0	0.00%	0	0	0	0	0	0	0	0
Roof	1	0.03%	-	-	-	-	-	-	-	-
Infiltration	-13	-0.26%	-	-	-	-	-	-	-	-
Lighting	380	7.87%	-	-	-	-	-	-	-	-
Power	185	3.82%	-	-	-	-	-	-	-	-
People	231	4.78%	-	-	-	-	-	-	-	-
Plenum	0	0.00%	-	-	-	-	-	-	-	-
Total	**4,829**	**100%**	**0**	**-54**	**4,099**	**0**	**0**	**0**	**0**	**0**
Heating Components	**Total (Btu/h)**	**Percentage**	North (Btu/h)	South (Btu/h)	East (Btu/h)	West (Btu/h)	Northeast (Btu/h)	Southeast (Btu/h)	Northwest (Btu/h)	Southwest (Btu/h)
Wall	733	32.61%	0	436	297	0	0	0	0	0
Window	864	38.46%	0	0	864	0	0	0	0	0
Door	1,389	15.11%	0	0	0	0	0	0	0	0
Roof	276	12.30%	-	-	-	-	-	-	-	-
Infiltration	374	16.63%	-	-	-	-	-	-	-	-
Total	**2,248**	**100%**	**0**	**436**	**1,162**	**0**	**0**	**0**	**0**	**0**

Fig. 60: Heating/Cooling load calculations in BIM for the master bedroom (Revit)

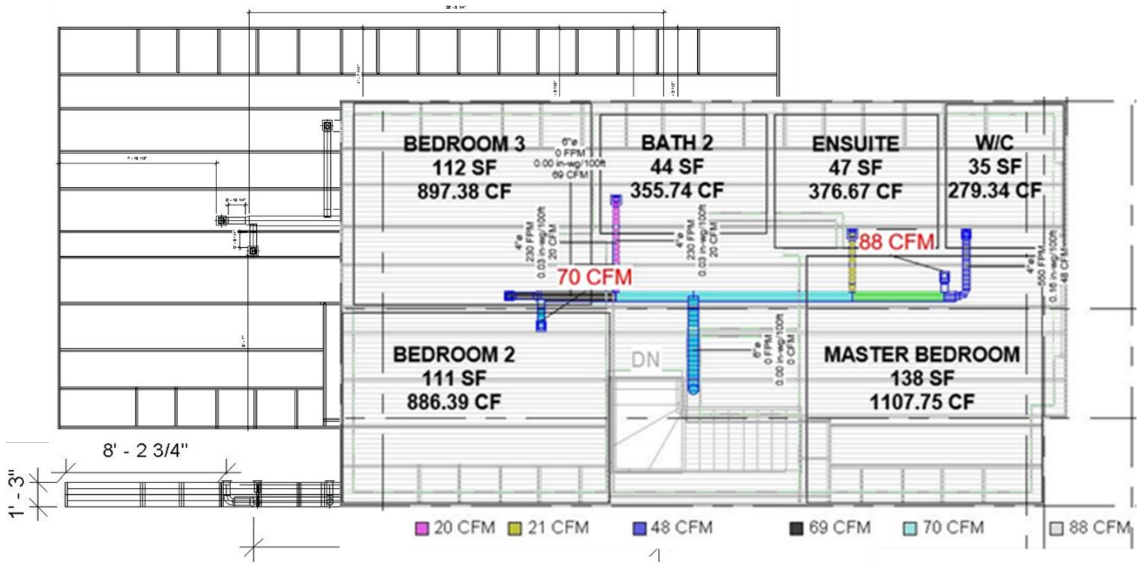


Fig. 61: Plan view of the designed system and the computed flow rates (Revit)

The load calculations indicate that the maximum flow rate required for this space is 88 CFM, which meets the space heating requirements during the peak load intensity. Based on this information, the floor-mounted register will be assigned a specific flow rate of 88 CFM (Figure 61). This input is used for sizing the system. After each air terminal is assigned a specific flow rate, the duct sizing must be done using a variety of methods discussed in the literature review. The available automated methods for duct sizing function in Revit are on equal friction and velocity. The following Figure 62 demonstrates the duct sizing function, which is a feature available in Revit to assists with detailing the design.

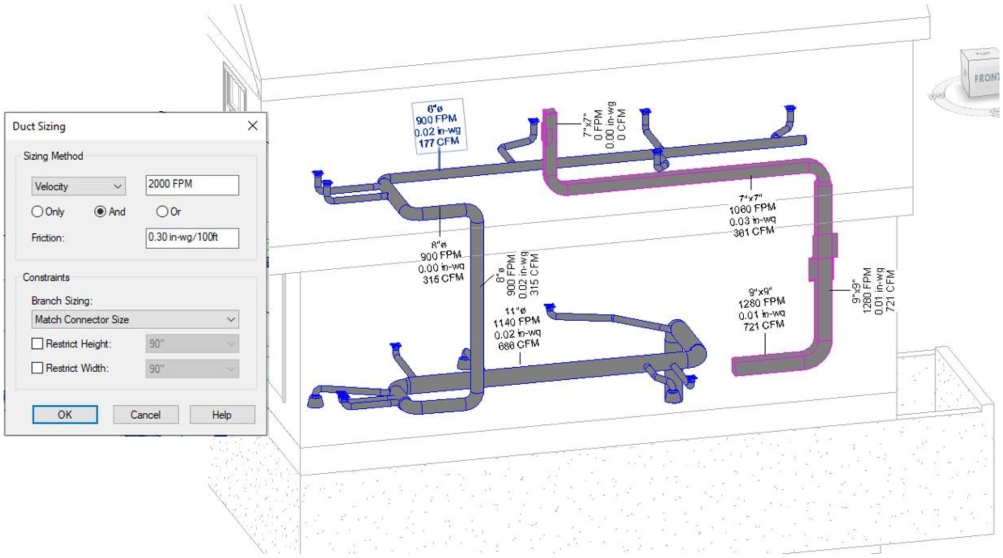


Fig. 62: 3D view illustrating the duct sizing function using the equal friction method and assigning high velocity (Revit)

Quantity Takeoff

After executing the final Dynamo module, the proposed methodology is complete, and the entire ductwork layout is created in the Revit BIM model. BIM estimates how much duct is required to be fabricated with a high degree of certainty. The quantity takeoff can be done by utilizing the BIM model and exporting the ductwork schedule. The total area of the sheet metal required for fabricating the ductwork system is calculated using standard galvanized steel gauge sizes. The cost of the system is a function of the total weight of the ductwork in pounds. As described in Chapter 3, the RSMeans database is used to evaluate the total time and cost associated with the project [27]. The following Figure 63 displays the exported ductwork schedule from Revit based on the case study one.

AUTODESK® REVIT® Floor Panel 1

<Duct Fitting Schedule>

A	B	C	D
Count	Family	Size	Type
1	Round Takeoff	4"ø-4"ø	Standard
1	Round Takeoff	4"ø-4"ø	Standard
1	Round Takeoff	4"ø-4"ø	Standard
1	Round Elbow	4"ø-4"ø	1 D
1	Round Takeoff	4"ø-4"ø	Standard
1	Rectangular to Rou	4"x4"-4"ø	45 Degree
1	Round Elbow	4"ø-4"ø	1 D
1	Rectangular to Rou	4"x4"-4"ø	45 Degree
1	Round Elbow	4"ø-4"ø	1 D
1	Rectangular to Rou	4"x4"-4"ø	45 Degree
1	Round Elbow	4"ø-4"ø	1 D
1	Rectangular to Rou	4"x4"-4"ø	45 Degree
1	Round Elbow	4"ø-4"ø	1 D
1	Rectangular to Rou	4"x4"-4"ø	45 Degree
1	Round Takeoff	4"ø-4"ø	Standard
1	Rectangular to Rou	4"x4"-4"ø	45 Degree
1	Round Elbow	4"ø-4"ø	1 D
1	Round Elbow	6"ø-6"ø	1 D
1	Round Takeoff	6"ø-6"ø	Standard
1	Rectangular to Rou	6"x6"-4"ø	45 Degree
1	Rectangular to Rou	6"x6"-4"ø	45 Degree

<Duct Schedule>

A	B	C	D	E	F
Count	Size	Area	Length	pounds per sqft of	pounds of duct
1	4"ø	0.08 m²	0.26 m	0.07 kN/m²	1.32 lb
1	4"ø	0.37 m²	1.17 m	0.07 kN/m²	5.90 lb
1	4"ø	0.21 m²	0.66 m	0.07 kN/m²	3.33 lb
1	4"ø	0.23 m²	0.73 m	0.07 kN/m²	3.69 lb
1	4"ø	0.00 m²	0.01 m	0.07 kN/m²	0.07 lb
1	4"ø	0.10 m²	0.32 m	0.07 kN/m²	1.62 lb
1	6"ø	0.52 m²	1.08 m	0.07 kN/m²	8.17 lb
1	6"ø	3.03 m²	6.33 m	0.07 kN/m²	47.68 lb
1	4"ø	0.05 m²	0.17 m	0.07 kN/m²	0.86 lb
1	4"ø	0.05 m²	0.17 m	0.07 kN/m²	0.86 lb
1	4"ø	0.05 m²	0.17 m	0.07 kN/m²	0.86 lb
1	4"ø	0.05 m²	0.17 m	0.07 kN/m²	0.86 lb
1	4"ø	0.04 m²	0.12 m	0.07 kN/m²	0.61 lb
1	4"ø	0.05 m²	0.17 m	0.07 kN/m²	0.86 lb
Grand total: 14		4.87 m²	11.56 m		76.69 lb

<Air Terminal Schedule>

A	B	C	D
Count	Family	Flow	Size
1	M_Supply Register	20 CFM	4"x4"
1	M_Supply Register	21 CFM	4"x4"
1	M_Supply Register	48 CFM	4"x4"
1	M_Supply Register	88 CFM	4"x4"
1	M_Supply Register	69 CFM	4"x4"
1	M_Supply Register	70 CFM	4"x4"

Fig. 63: Material quantity takeoff extracted from the 3D model (Revit)

The total weight of the system is 355.33 lb. This value is automatically calculated based on the 3D model and the material properties of the ducts. According to RSMeans [27] section 23.31.13.13.05.20, the construction of metal ductwork from 200 to 500 lb. Requires a crew of two sheet metal workers and one sheet metal apprentice, resulting in a daily output 245 lb., or 0.098 labor hours. This means that the total job should be completed in 1.85 days, resulting in a total of 34.8 paid work hours. According to the RSMeans, the cost for completion will be $1193.91, including the overhead and profit. ACQBUILT pays an average of $35 per man-hour, which would result in a similar cost. The total time of construction in the factory environment is different from traditional site-construction. The workers install the ductwork inside the floor panels on the specific workstation, which does not require over-the-head installation. RSMeans assumes a height of installation of less than 10' for the productivity analysis, and additional installation height would add a percentage to the cost and time calculations. Therefore, it is adequate to use RSMeans for the comparison of the case study results, with the original design and construction data provided by ACQBUILT.

Results and Comparison

Just like the original design offered by ACQBUILT, the generated air distribution system provides each space with a floor-mounted or a ceiling supply register based on the user input. Also, the developed system allocates a central return air system in the appropriate mechanical walls. The performance of the new layout will meet all the HVAC requirements of the original design while promoting improvements in terms of three measurable objectives: reducing the length of the ductwork, reducing conflicts with the structural system, and reducing the MEP system overlaps. The objectives aim to reduce the total construction time and cost for each project. The ACQBUILT prefabrication plant is capable of producing framing components for wall, floor, and roof panels of three houses in an 8-hour shift. A facility with such a high production rate is interested in increasing the speed of installation of the HVAC system to meet the requirements of fast-track construction and delivering the projects more efficiently. The overview of job hours provided by the manufacturing company indicates that the average number of hours used for the construction of an HVAC system in the factory environment is between 53.14 to 81.85 hours (Figure 64).

LEGACY'S

JOB	ADDRESS	FL 1	FL 2	WALLS	Rough-I	DUCTS	FINAL	RETURN	
20KSW-19-0028	[illegible]								0
20GLR-19-0029	[illegible]							4	4
20GRH-19-0031	[illegible]						8		8
20KSW-19-0033	[illegible]					26.5	8		34.5
20KSW-19-0034	[illegible]	4	5		9.5	32	9	6.5	66
20GRH-19-0037	[illegible]	6	5		16	35.5			62.5
20ROS-19-0040	[illegible]	6	4		12	34	14	3	73
20KSW-19-0043	[illegible]	5	5		6	12	6		34
20KSW-19-0045	[illegible]	6	2		7	25	5	2	47
20GRH-19-0047	[illegible]	7	3		10	34	10	1	65
20KSW-19-0035	[illegible]	5	3.5		10	42.5	9		70
20KSW-19-0044	[illegible]	7	4		8	31.5			50.5
20GRH-19-0048	[illegible]	6	4		8.5	22.5	10		51
20LAG-19-0050	[illegible]	6	5		12	23	5.5		51.5
20LAG-19-0051	[illegible]	4	5		8.5	8.5	5		31
20MCR-19-0055	[illegible]	4	4		13.5	13.5			35
20GLR-19-0061	[illegible]	4.5							4.5
20GRH-19-0053	[illegible]	4.5	4.5		17.5	29.5			56
20ROS-19-0054	[illegible]	4	4		8.5	18		1.5	36
20-LAG-19-0058	[illegible]	5	6		8.5	36.5			56
20LAG-19-0057	[illegible]	4	4		10	26		1	45
20KSW-19-0059	[illegible]	4	4		8.5	21		2	39.5
20-GRH-19-0046		6	4		2	28	6		46
20-LAG-19-0051		6.5	5		8.5	28.5			48.5
20MCR-19-0064		5	9		9	10.5			33.5
20KSW-19-0061		4	5		7.5	10			26.5
[illegible]		7	4		9	17			37

LEGAL SUITE/FIN BSMT

JOB	ADDRESS	FL 1	FL 2	WALLS	Rough-I	DUCTS	FINAL	RETURN	
20ROS-19-0042	[illegible]	5	7		21.5	68.5		2	104
20GLR-19-0046	[illegible]	4	3		9	20	3	2	41
20KSW-19-0049	[illegible]	9	4		20.5	17.5			51
20ROS-19-0052	[illegible]	4	4.5		10	30			48.5
20MCR-19-0056	[illegible]	7	3		8.5	40.5		20	79
									0
									0
									0
									0
									0
									0
									0
									0
									0
									0
									0
									0
									0
									0
									0
									0
									0

CLASSICS

JOB	ADDRESS	FL 1	FL 2	WALLS	Rough-I	DUCTS	FINAL	RETURN	
10ATR-19-0065	[illegible]	5	8		8	40		2	63
10-WSM-19-0053		6.5							6.5
10-WSM-19-0066		3	5		8	19			35
10GLR-19-0061					6				6
10ATR-19-0057									0
10GLR-19-0069		6	5						11
10KSW-19-0058		6	4		12				22
10ATR-19-0072		3.5							3.5
10WSM-19-0070		10							10
10LAC-19-0079		6	6						12
10LAC-19-0080		5	2						7
10DES-19-0048		5							5
10ATR-19-0074		5							5
10DES-19-0082		4.5	7						11.5
10WSC-19-0075		4							4
10DES-19-0076		6							6
10ROS-19-0064		6	6		10	32		1	55
10GLR-19-0077		5							5
10WSM-19-0071		0	7						7
10ATR-19-0073		5	5						10
10WSM-19-0085		5							5
10DES-19-0068		4							4
									2.5

Fig. 64: HVAC job hours overview (courtesy of ACQBUILT, Inc.)

The following table 1 compares the associated time and cost estimations for the construction of the proposed designs to those of the original designs. The total potential savings is attributed to the total material; cost and time saving are highlighted to demonstrate the benefits of the applied methodology. For each project, the identified design conflicts are reduced, producing a more efficient ductwork layout that requires less material and construction time. Each project has the potential for improvement, and the proposed methodology improves the design of the ductwork systems to make them easier and faster to install in a factory environment.

Table 3. Result and comparison of the optimized designs vs. the original designs

			Original Design						Proposed Design Alternative					
Job	Type	Size (Sqft)	Total Length (ft)	Total Holes in Beams	Total MEP Overlaps	Total Duct Weight (lb)	Man-Hours (hrs)	Cost	Total Length (ft)	Total Holes in Beams	Total MEP Overlaps	Total Duct Weight (lb)	Man-Hours (hrs)	Cost
Niagara	Detached Garage	1200	140’ 10”	20	2	453.65	44.5	2839.56	109’ 11”	15	0	355.33	34.8	2220.81
Florance	Detached Garage	1650	215’ 4”	32	5	714	67.5	4332.91	181’ 3”	25	3	573.27	54	3467.81
Glasgow	Detached Garage	1762	183’ 7 ½ “	29	3	534.27	52.3	3226.99	161’ 5 ½ “	24	2	425.06	40.5	2686.94
Kingston	Attached Garage	1723	156’ 6 ½ “	22	9	396.15	38.8	2478.44	133’ 7 ½ “	21	7	360.28	35.8	2283.44

These results highlight the total savings in terms of the duct length, intersection with the structural system, and the MEP conflicts that the design layout solves. The total cost and duration of the projects are estimated and compared using the RSMeans building construction database [27].

Niagara Model – This project is the smallest in size. However, the job overview indicates that there was a total of 70 hours spent on finishing this job. The most time-consuming task was the installation of the ducts and the rough-in. It is speculated that this could have been due to the large number of holes required in the project, and due to space limitations, there would be more time spent by the laborers in the congested MEP locations. According to RSMeans [27], this job should only take 44.5 hours with the original design. Nevertheless, the design of the air distribution system was optimized, and the total duration is estimated to take 34.8 hours, which could potentially save 9.7 hours. After the new design is generated with the proposed methodology, the total length is reduced by 9.51 m (22%). Five intersections with TJI Joists were eliminated, representing a 25% reduction in drill-through holes in the structure. Furthermore, the plumbing and the ductwork do not overlap, thereby eliminating MEP congestions. All the improved objectives aim to improve the constructability and help standardize the construction tasks. Total cost saving is estimated to be $618.75.

Florence Model – After applying the proposed methodology and generating the alternative design, the total length is reduced by 10.6 m (15%). Seven intersections with TJI Joists were eliminated, representing a 22% reduction in drill-through holes in the structure. Furthermore, the plumbing and ductwork overlaps are avoided in two locations, thereby reducing MEP congestions by 40%. The total estimated construction time is reduced by 13.5 hours, and the total savings is estimated to be $865.1.

Glasgow Model – The total length is reduced by 6.76 m (12%). Five intersections with TJI Joists are eliminated, representing a 17% reduction in drill-through holes in the structure. Furthermore, the plumbing and the ductwork overlaps are avoided in one location, thereby reducing the MEP congestions by 33.33%. The total estimated construction time is reduced by 11.8 hours, and the total savings is estimated to be $540.05.

Kingston Model –This project consisted of good design with minimum conflicts with the structure and efficient use of duct material. Therefore, applying the proposed methodology reduced the total duct length by only 6.54 m (13.6%), and only one intersection with TJI Joists is eliminated, representing a 4.5% reduction in drill-through holes in the structure. Furthermore, the plumbing and the ductwork overlaps are avoided in two locations, thereby reducing the MEP congestions by 22.22%. The total estimated construction time is reduced by 3 hours, and the total savings is estimated to be $195.

Results and discussion

Each project varies in size and HVAC design requirements. The ductwork layout complexity is dictated by the architectural model and the structural and MEP constraints. Therefore, the total cost and duration of each project are directly affected by the design and construction of the air distribution system. The total cost for the material and labor is calculated based on the quantity of ductwork required to be installed, measured in pounds of sheet metal. By applying the proposed methodology, the designed systems are optimized, and each project requires less ductwork to be installed with fewer conflicts, making the installation tasks easier and faster to improve constructability and productivity. The following points highlight the results and findings associated with each case study.

- The total cost associated with the original design of the four houses is $10,999.46, and the optimized design can reduce this cost to $8,375.56, promoting $2,623.9 (23.83%) in savings.
- The total duration for completing the four jobs is 164.4 hours with the original design, and with the optimized designs, the total duration can be reduced to 129.3 hours, saving 35.1 hours (21%) in construction time.
- A total of 18 interferences between the duct path and the with TJI Joists is eliminated, representing a 17.5% reduction in drill-through holes in the structure and less construction waste.

- The plumbing and the ductwork overlaps are avoided in 7 locations, thereby reducing MEP congestions by 36.84%
- 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 developed optimization algorithm in the Dynamo modules. The proposed methodology can help engineers identify alternative design solutions that will result in more efficient construction processes.

Chapter 5: Conclusion

5.1 General Conclusion

Regardless of the size of the building project, MEP 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. HVAC systems, specifically the heating systems, are essential within the cold climates, specifically in the Canadian environment, and they encounter the majority of the utility bills in the life cycle performance of the buildings as well as the significant portion of the cost induced during the construction. Panelized and modular construction methods aim to decrease the cost and duration of a project; however, they encounter challenges in the installation of the MEP systems in the offsite environment due to the complexity of the system configurations and lack of precision in the designs. The main contribution of this paper is to provide designers with a tool that will consider construction parameters and factor the challenges of offsite construction in the design drafting stage. The benefits of this contribution include the coordination of MEP elements with respect to the architectural constraints as well as increasing potential for prefabrication by designing a system tailored to meet the offsite construction requirements.

This research proves that with appropriate planning for the ductwork layout, a significant amount of work for the installation will be reduced. By integrating the BIM model with the decision-making algorithm and GA optimization, the designed layout will use minimum ductwork to complete the system requirements and results in save in material as well as reduce the construction waste. Optimizing the design of the ductwork layout also reduces the interferences between the ducts and the structural members. By reducing the ductwork and the structural conflicts, the laborers will spend less time cutting holes through the beams for fitting the ducts. In the project case studies, it was concluded that less construction waste would be produced because there is less conflicts and less cut out holes that are required to be made in the timber joists. This will be an advantage to modular construction where the installation tasks of the ducts will become more repetitive and less time-consuming. Eliminating the risk of congestions between the ductwork and the MEP systems is another benefit of the optimization technique. Without conflicts and overlapping of the designed building systems, the installation task of each trade will be done in parallel, and the crews will not be interrupted, thereby increasing productivity and efficiency on the assembly line. With the proposed optimization performed in the design stage, the variance in the processing time of tasks on the manufacturing line will be reduced, and the potential for prefabrication will be increased with less risk of conflicts and the need for rework.

Generative design in BIM assists the designer in quickly evaluating design alternatives and saving time with automation. Automation in design and drafting can eliminate time-consuming tasks. Design calculations and 3D drafting are automated in the proposed methodology to allow the manual work to be shifted to more critical tasks. The main contribution in this paper is employing generative computer design to reduce the risk of construction conflicts and increase productivity in the design and construction phases of an air distribution system layout. Assessing alternative solutions during the planning stage will allow the construction process to be applied with more certainty in the outcome. This results in fewer change orders and less time wasted between 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 concept of applying optimization techniques for generative design in Revit creates a more user-friendly interface that can be adapted for most projects easily with minimum training required. The benefits and the findings in this research can be summarized in terms of the total material saving, total cost-saving, and increasing the productivity in the assembly line. Based on the case study results, the industrial collaborator can potentially decrease the cost from $10,999.46 to $8,375.56 and the duration of the projects from 164.4 man-hours to 129.3 man-hours saving $2,623.9 and 35.1 man-hours between the four case studies. It is stated that the collaborating prefabrication company ACQBUILT is capable of manufacturing 8-9 houses per day, and if we assume that only these four houses are being manufactured the overall saving can add up to approximately $ 2,218.9 per day, $ 11,094.5 per week, $44,378 per month and $532,536 a year if 1920 units are manufactured.

5.2 Summary of Contributions

There have been several studies on the coordination of the MEP systems and the potential benefits of implementing BIM for prefabrication. Many studies also focus on the modularization of the MEP elements in offsite construction for industrial settings. However, there is no research established in the area of residential design of air distribution system layout for prefabricated buildings. This research successfully utilized BIM and optimization techniques to establish a framework for the design of the air distribution system for panelized and prefabricated housing to increase design accuracy and construction efficiency. The contributions are summarised as follow:

i. Necessary groundwork for the development of a methodology to decrease HVAC project time, cost, and waste in panelized housing.

ii. Reduced variation in designs for more rapid construction with details for offsite coordination of the ducted system.

iii. Parametrized and a knowledge-based framework to achieve a high-performance system and maximum occupant’s comfort with standardized design processes in BIM.

iv. Automated process for designing and modeling the air distribution layout instead of relying only on the designer and contractor's experience to reduce manual error and drafting time.

v. Optimization of ductwork layout to bridge the gap between design processes and constructability analysis with automatic coordination and conflict resolution in BIM.

5.3 Limitations and Future Works

The main purpose of this research was to lay the groundwork and develop a methodology to increase design efficiency and improve the construction productivity of air distribution systems in prefabricated residential buildings. There are shortcomings that can be addressed accordingly to advance this research for solving other design and construction challenges. These shortcomings can be solved by expanding the proposed methodology step-by-step, where it is applicable.

Limitations:

i. The proposed design procedure is limited to the location of the air terminals and the ductwork layout with 90-degree fittings. Other factors, such as the location of the fans and the damper and other types of fittings, are not considered.

ii. The performance and efficiency of the air distribution system are limited to occupant's comfort on the basis of the ADPI selection guide, which does not consider humidity, radiant temperatures of surrounding surfaces, metabolic rate and clothing insulation of the occupants are not considered.

iii. The established framework is solely based on Revit modeling, and not all companies use Revit.

iv. GA is the sole optimization algorithm used in this research because it is widely used in construction management and HVAC optimization challenges and easily understood for the sake of future development. It is recommended to assess the benefits and shortcomings of GA optimization with other methods such as multi-start and particle swarm optimization techniques to discover the best suitable method for this field.

v. This methodology only considers the ductwork layout configuration. In order to improve productivity at a higher rate, the same procedures should be applied to other MEP elements such as the plumbing and the fire protection system to decrease the construction time and have an integrated solution that meets the prefabricated construction methods for all given building services.

vi. This study is limited to medium size single-family houses. The methodology should be expanded to be able to process commercial and industrial air distribution system's design requirements, which are, in turn, more costly and much more complex. To further assess the potential of the proposed methodology, larger and more complex projects such as hotels, community centers, and schools should be investigated to assess the degree of savings that can be promoted based on the scale of the projects.

Recommendations for future work:

i. A Time study should be conducted in the field to evaluate the true measure of cost and time values in order to assign weights for the objective function.

ii. The location of the fans and the damper and different fittings should be accounted for because each element contributes to the project cost and performance.

iii. The energy costs are not yet included, which are valuable for predicting life cycle costs.

iv. Consider Industrial Foundation Classes (IFC) to extend the application of the BIM

v. Other building services, such as the plumbing and fire protection system, can also benefit from layout optimization techniques like the one proposed for the ductwork layout.

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