An Investigation of Generative Design for Heating, Ventilation, and Air-Conditioning

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ABSTRACT

Energy consumption in buildings contributes to 41% of global carbon dioxide emissions through electricity and heat production, making the design of mechanical systems in buildings of paramount importance. Industry practice for design of mechanical systems is currently limited in the conceptual design phase, often leading to sub-optimal designs. By using Generative Design (GD), many design options can be created, optimized and evaluated, based on system energy consumption and life-cycle cost (LCC). By combining GD for Architecture with GD for HVAC, two areas of building design can be analyzed and optimized simultaneously, resulting in novel designs with improved energy performance. This paper presents GD for HVAC, a Matlab script developed to create improved zone level mechanical systems for improved energy efficiency. Through experiments, GD methodologies are explored and their applicability and effect on building HVAC design is evaluated.

Author Keywords

Generative Design; Genetic Algorithm; Heating, Ventilation, and Air-Conditioning; HVAC

ACM Classification Keywords

J.2 Computer Applications: PHYSICAL SCIENCES AND ENGINEERING; J.6 Computer Applications: COMPUTER-AIDED ENGINEERING

1 INTRODUCTION

Industry practice for the design of mechanical systems in the conceptual phase is limited [5]. Current practice is to select a base design to iterate on. This initial design is often a design previously used by the designer for other projects. To accommodate specific requirements, adjustments are made to the base design as the project proceeds. These adjustments, some of which occur during the construction phase, are often not cost effective, and can lead to inefficient solutions. This common practice of dealing with problems as they arise jeopardizes the potential efficiency of the mechanical system and is exemplified by the significant amount of building energy consumption globally. This paper outlines a methodology utilizing genetic algorithms to develop more optimal HVAC systems, enabling the creation and evaluation of many novel designs during the conceptual phase. By considering and evaluating more designs, more advantageous options can be discovered and selected prior to construction.

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2 RELATED WORK

GD is a method that mimics the human approach to design through an algorithmic methodology. Normally, design begins with a set of ideas developed into a design. Throughout the development process, designs are evaluated and improved, by adding new design parameters and constraints, to create a new design iteration. In a similar fashion, GD starts with an initial design or idea, which is then developed into a rule set. The rule set is turned into source code that generates multiple design solutions. With the completed designs, a designer can either alter the source code or the original rule set, depending on how results are evaluated. Figure 1 demonstrates the GD process.

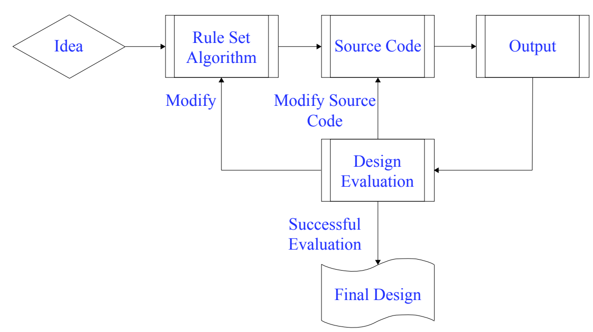

Figure 1. A Flow Chart Representing the Concept of Generative Design

Gu, Singh, and Merrick [10] identify four different GD techniques: shape grammars (SG), L-systems (LS), cellular automata (CA), and genetic algorithms (GA). GAs are a method for solving both constrained and unconstrained optimization problems and are comparable to the concept of evolution by natural selection in biological systems [7]. Of these methods, GAs have been successful at solving various HVAC optimization problems. This can be attributed to the fact that building optimization problems contain several characteristics limiting the applicability of both direct search methods and gradient-based optimization methods [16].

"Some characteristics that building optimization problems may include are a mixture of a large number of integers and continuous variables, non-linear inequality and equality constraints, a discontinuous objective function and variables embedded in constraints that are not in the objective function." [5]

As a result, GAs are prime candidates for solving building optimization problems. Furthermore, GA's possess the ability to identify optimal trade-offs among multi-objective optimization problems, necessary when considering both energy consumption and LCC.

2.1 Genetic Algorithms

GAs are an optimization strategy based on evolution by natural selection [7], where each candidate solution in the optimization problem is represented by a coded representation of design attributes, analogous to a *chromosome* [1].

GAs create an initial, random population set of these solutions, and continuously iterate until the near-optimal is determined. The five main operations in the iteration process are: evaluation of the fitness function, selection, crossover, mutation and replacement [1]. The effectiveness of each design at solving the problem is determined by its *fitness* [1]. Figure 2 demonstrates the GA process.

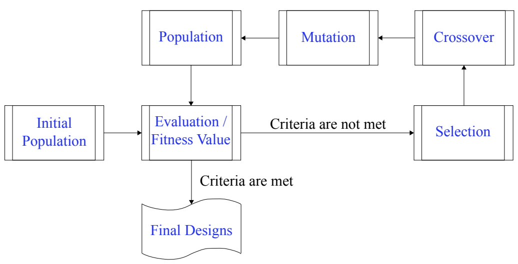

Figure 2. A Flow Chart Representing the Concept of a Genetic Algorithm

Replacement

An initial randomized design population is generated. If the fitness criteria are not met, a new population set is created based on crossover and mutation operations. A new population replaces the old population which is then re-evaluated.

Crossover

An operation that exchanges an aspect of one design with one from another design. This operation is performed probabilistically, and may not occur during a given iteration.

Mutation

An operation that alters an aspect of a design option. For example, if solutions are represented as binary values, a mutation will change the attribute from 0 to 1 or vice versa. Mutations are responsible for keeping variation in the design set and can result in radically different solutions between generations.

Fitness Value

Each design is evaluated and assigned a fitness value based on how well it satisfies the constraints of the given problem. The constraints of the problem can be single-objective or multi-objective during the optimization process.

Selection

The selection operator is used to select design solutions from the current population that will succeed to the next round/iteration. Selection criteria vary, and can include: best single solution, the best in a set of solutions, or even a random selection of solutions.

2.2 Previous Genetic Algorithm Applications

Variations of GAs have been developed and applied to solve energy optimization problems. Caldas et al. [5] developed a Pareto-based genetic algorithm to optimize aspects of building design, resulting in reduced cost and time, while still achieving a desirable design. Their optimization strategy was applied to three areas of building design: building envelope, building form, HVAC design and operation. GA's that utilize the Pareto concept have also been used successfully in energy and building studies (Hamdy et al. [11]).

Different GA methodologies can be applied to the same optimization problem leading to similar results. Palonen et al. [13] applied an elitist non-dominated sorted genetic algorithm (NSGA-II) to the architecture and HVAC system of a Finnish residential house. Hamdy et. al. [11] studied the same residence and instead, applied a modified multi-objective genetic algorithm (PR_GA), utilizing a Pareto-based approach combined with the IDA-ICE 3.0 simulator [11]. This multi-objective problem was focused on lowering the CO2 emissions while maintaining realistic investment costs. Ultimately, the NSGA-II yielded similar results to the modified PR_GA [11] in several runs, appearing to be the most efficient of the GAs according to Deb [8].

Additional studies have been completed that range in GA types: segregated genetic algorithm (SGA), simple genetic algorithm, multi-island genetic algorithm (MIGA), and micro-GA. The SGA was used to route and size ductwork, and was tested using the duct layout in Chapter 32 of ASHRAE (1997) [1]. A modified version of the 'simple genetic algorithm' described by Goldberg was developed to size components in an HVAC system with the goal of reducing the systems life cycle cost [15]. Alvaro Siza's design of the School of Architecture in Oporoto, Portugal was analyzed through a genetic system (GS) that consisted of a micro-GA and used DOE-2.1E as the fitness calculator [4]. The development was created to establish the effect that design choices had on energy consumption. In the end, it suggested similar architectural designs as Siza, but also some varied design concepts, suggesting that the GS could indeed be a beneficial method for exploring various design options during the conceptual design phase. Brahme et al [3] employed differential modeling, homology-based mapping, and generative design agents, to allow the use of building performance analysis tools early in the design. This development was utilized in an office building in Pittsburgh where it generated duct routing options based on equipment location.

3 PROPOSED METHODOLOGY

In previous work, GAs have been utilized to optimize some aspects of HVAC design, however, complete GD for HVAC has not been widely explored. Barnaby et al. [2] explored an automated HVAC system design tool, but design was completed using standard industry practices. In contrast, the proposed approach considers the system from base parameters and diverges from traditional techniques to find novel designs. These base parameters can be categorized for zone-level design, and include the generation and evaluation of:

1. Building thermal zones
2. Type, number, size and location of diffusers and return grills
3. Sizing and routes of both supply and return ductwork
4. Sizing and location of equipment
5. Sizing and routes of exhaust ductwork
6. Sizing and location of the intake and exhaust louvers
7. The fitness of each design option

Once the building information model (BIM) is available, the required information needs to be extracted. This is currently done manually, however, a gbXML file format can be exported from Autodesk Revit and imported into the Matlab script to obtain all of the required information. Once the information is gathered, the potential thermal zones need to be determined. A thermal zone is defined as an area in the building which has its own temperature control [6]. For each zone, an algorithm determines the type of room, room load requirements, room orientation, and room adjacency when grouping rooms into thermal zones. Figure 3 displays the concept of rooms having to be the same type, orientation and adjacent to each other in order to have a chance to be grouped together.

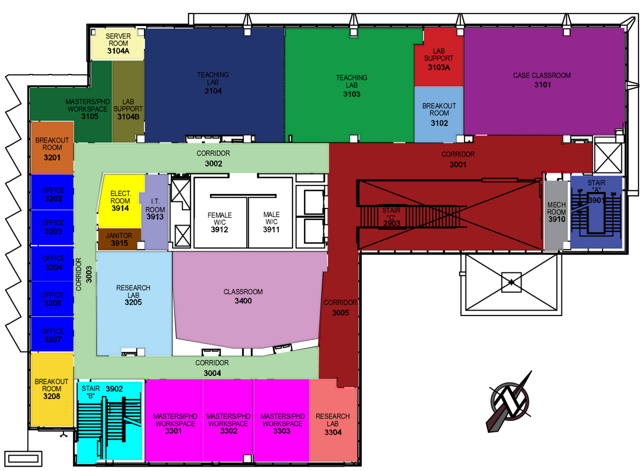

Figure 3. Example zoning for the third floor of the Canal Building

Room Type

The type of room is important when exploring zoning options. Some rooms cannot be zoned together due to certain codes and standards i.e. bathrooms require their own exhaust systems as they are in the third air class category and air can only be recirculated within its own zone (ASHRAE Std 62.1).

Even when building code allows room types to be grouped together, some combinations should be avoided as they can result in system inefficiency for both heating and cooling seasons i.e. grouping a single occupant office with a multi-occupant office can be problematic depending on the control strategy. If the single occupant office contains the lead thermostat, the multi-occupant office will not be supplied with enough cooling to meet the demand from occupant gains. On the other hand, if the multi-occupant office contains the lead thermostat, the single occupant office may be supplied with an unnecessary amount of cooling. Room averaging could be employed, however, this would result in the single occupant office being over-cooled and the multi-occupant office being under-supplied during cooling mode.

Room Load Requirements

It is important to group rooms together that require similar heating and cooling. A larger discrepancy between required heating and/or cooling for a room will either lead to an unnecessary amount of energy being expended on one room at times, or will lead to uncomfortable occupants. This would result from unsatisfactory amounts of cooling and/or heating being supplied to the other room, depending on the controls scheme, similar to the example in the Room Type section.

Chapter 18 of the 2013 ASHRAE Fundamentals Handbook outlines two methods for estimating the peak heating and cooling load requirements, the heat balance (HB) and radiant time series (RTS) methods [6]. Peak load calculations can be thought of as worst-case scenarios, meaning that the peak cooling occurs when all possible internal gains are present, and the solar radiation and outdoor air temperature are at their highest. However, heat gains from infiltration can be neglected for commercial buildings when positive air pressure can be assumed [6]. Conversely, the room's heating load requirement is calculated in the middle of the night when no solar gains and internal heat gains are present, the outdoor air temperature is at its lowest, and losses due to infiltration are taken into consideration. Once the heat gains are calculated separately utilizing the RTS approach, they can be summed together, resulting in Equations 1 and 2.

$$Q_{PeakHeating} = Q_{Ext} + Q_{Inf} \tag{1}$$

$$Q_{PeakCooling} = Q_{Ext} + Q_{Solar} + Q_{PL} + Q_{L} + Q_{Occ} \tag{2}$$

Several tables from ASHRAE Fundamentals are utilized within the code to determine the internal heat gains from occupants, lighting, and computers. Table 2, section 18.4 [6] represents the energy rate from occupants performing various activities. Standard practice is to assume that the number of occupants present during peak load is equal to the number of seats assigned by the architect. Heating loads due to equipment, specifically desktops and laptops are calculated based on ASHRAE table 8, section 18.11 [6]. Offices are assumed to have one desktop per occupant, and meeting rooms are assumed to have one laptop per two occupants. Maximum lighting per room type is determined from ASHRAE table 2, section 18.5 [6] and used for light heating gains during peak cooling operation. This methodology mainly follows standard industry practice, following the ASHRAE guidelines, however, the outdoor temperatures, and maximum solar radiation based on building location are determined by utilizing the Canadian Weather for Energy Calculations (CWEC) file.

Room Orientation

Although orientation plays a role in the required load for a room it is important to evaluate individually as well. Consider a zone that consists of two offices: one facing south and the other a south-west corner office. These offices might have similar peak load requirements, but in the late afternoon the corner office will be effected by solar gains at a magnitude that the south office will not experience. However, the south office would unnecessarily receive the same amount of cooling as the corner office during this time in the summer.

Room Adjacency
Although rooms may meet the other three requirements, it is key to examine the grouping possibilities from a practicality standpoint. If one office is nearly on the opposite side of the building, the routing of the ductwork would be almost impossible to construct, and unnecessarily extensive duct runs will decrease the efficiency of the system.

Consider Figure 4, a script was developed which thermally zoned offices based on similar load requirements [14]. The south corner office has similar peak load requirements to two large classrooms on the north side due to the solar gains it receives, and were grouped together by the algorithm. If implemented, this grouping would result in difficult routing for ductwork and unreasonably long runs. Although peak loads are similar, the south corner office will only have similar loads to the northern classrooms during solar noon, and most of the time, will require significantly less cooling than the two laboratories. The problem will be exacerbated when the labs are filled with students and it is not solar noon. Considering the peak load requirements in isolation and neglecting adjacency for thermal zoning can have significant negative impacts on system design.

Figure 4. Thermal Zoning outcome from a previously developed algorithm showing unrealistic grouping of north and south rooms into a single zone.

The number of zones selected has a significant outcome on the initial cost of the building's mechanical system, the efficiency of the system, and the comfort of the future occupants. The more zones there are, the more terminal units are required and the more expensive the system. Secondly, requiring greater consideration as building design progresses, is the efficiency of the system. The least amount of zones possible will result in the least efficient design option, as the occupants will never maintain an identical schedule throughout the year, leading to times when the system is supplying tempered air to empty rooms in order to meet the demand of one office. Thirdly, and rarely considered, is occupant comfort. The more offices contained within a zone, the less control and customization each occupant will have over their comfort. For these reasons, the zoning options that are determined will depend on the relative importance of each of the input parameters, which must be determined prior to running the tool.

Mapping
After the generation of multiple zoning strategies, the HVAC configuration is determined using a mapping process. Figure 5 illustrates the output of the mapping process and displays the layout of nodal points, grid and adjacency lines, and zone boundary lines, similar to Brahme et al. [3]. As done by Brahme et al. [3] the adjacency lines represent the potential paths for ductwork. This methodology builds on the work done by Brahme et al. [3], as the nodal points represent the various options that the GA has when permuting locations for the diffusers, return grilles, and equipment, rather than just for the locations of the terminal units. In addition, this work did not include zone boundary lines which contain all rooms that will be grouped in the same thermal zone, as determined by the previous process. The zone boundary lines assist in the permuting of terminal units, whereas the locations of the terminal units were manually input to generate the duct routing in their case study [3] .

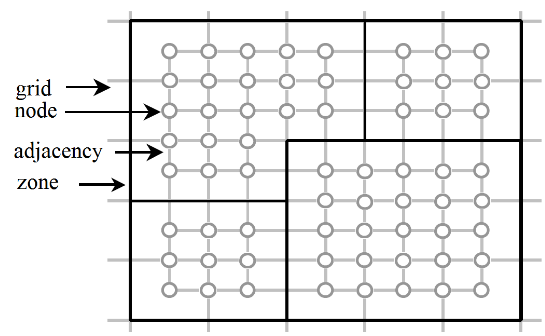

Figure 5. Example Building Mapping.

Due to the combinatorial explosion in the design space, it is important to introduce appropriate constraints, such as constraints on equipment sizing. Directly using the results of the peak load calculations from the *Room Load Requirements* section, results in equipment being sized at a capacity which is rarely required during a year. ASHRAE suggests using the 99th percentile outdoor air temperature when performing the heating load calculation. The justification here is that considerable fluctuations in weather conditions occur from year to year, and using worst case on record could often result in equipment with excess capacity [6] for most normal years. The ASHRAE fundamentals handbook [6] does not address the over-sizing of units that allow for cooled air to pass, such as variable air volume boxes (VAV). Although these terminal units might have to deal with peak cooling loads at some point during the year, it is usually a rare occurrence. Equations 1 and 2 are used to constrain equipment size. Generally, the GA attempts to minimize sizes, finding the smallest sizing for equipment without jeopardizing comfort during exceptional times of the year, but is constrained to stay within the limits set in these equations.

Diffuser and return grille mapping

At this point, a GA will generate variations for diffusers and return grilles, and determines the range of types, number, size and location within each zone as depicted in figure 6. Each population of diffusers and grilles is required to meet a single objective standard, based on a Computational Fluid Dynamics (CFD) study. Occupant comfort becomes a constraint, and designs resulting in large drafts are eliminated. Furthermore, designs that do not meet the functional requirements of the system will be eliminated from consideration i.e. one constraint is that each room will require at least one diffuser.

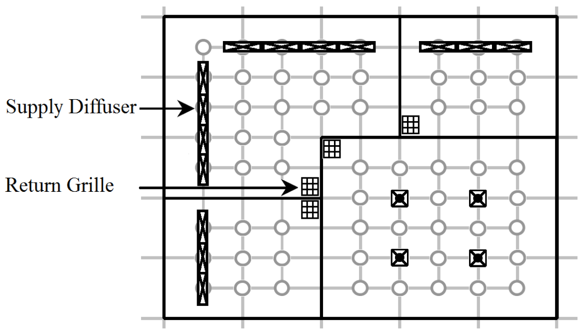

Figure 6. Example mapping of the supply diffusers and return grilles.

A GA will also be required to generate the equipment size and location. At this stage the corresponding supply duct sizing and routing will need to be completed. An example of this is depicted in Figure 7. Once this is completed, the return duct sizing and routing will be determined in a manner which does not interfere with the equipment and supply ductwork. Each design option at this stage will need to be tested for its fitness.

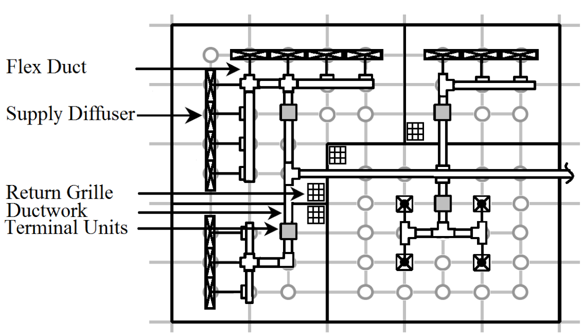

Figure 7. Example mapping of the HVAC system components.

Fitness at this stage is determined through a multi-objective approach utilizing building performance simulation (BPS) in conjunction with a LCC analysis. Each design option is evaluated using this approach. The building performance simulation is created based on the architecture and the design strategies that are generated. These design options will be evaluated based on annual energy consumption associated with the design.

The number of times that the system cannot meet the demand of the building, and the magnitude of deficit is also considered as part of the evaluation. For example, although an extremely under-sized system will not consume as much energy as an over-sized system, it will not be serving its purpose and will not be accepted. A system that does not always meet the demands of the zone could be accepted, for example it is not important to adequately supply cooling to the west façade offices around 7 pm in the summer since occupants have likely gone home.

The LCC of the system will be determined which considers the initial cost, the cost to operate, and the cost to maintain the system. The percent change between LCCs of each design option will be compared to the percent change of the energy consumption to allow for the most efficient design to be selected while remaining cost effective.

The design option's ability to solve the multi-objective problem, or rather its fitness is important to analyze, but it is also beneficial to quantify each design options feasibility/practicality. Designs that propose infeasible solutions ultimately will not be selected, however, slightly infeasible design options can be useful to pass through to the next generation of designs, as they can allow for a new area of the design space to be explored. Infeasible designs can be become feasible with slight variations (repairs) [1]. Different techniques for the introduction of infeasible solutions into the genetic variations can be addressed in different ways. The penalty method is generally considered the most successful method [1]. Alternatively, an SGA approach consisting of two population sets, one that utilizes a severe penalty and another that uses a limited penalty [12] can be employed, allowing feasibly and infeasible genes to interact.

As previously discussed, there is zero tolerance to impractical designs in the final solution set, meaning that each final design option must adhere to the Building Code and ASHRAE Standards, and all options that do not comply will be eliminated from consideration. The path and process to get to these solutions can include imperfections along the way and allow novel designs to be explored. Once the final design options have been determined it will be up to the mechanical designer to decide which design should be finalized utilizing his previous experience and knowledge. He/she will have to decide which design is the most practical and well suited for the given building, considering cost, and efficiency.

Although the above methodology is what is required to have a complete tool for the generative design of HVAC, critical design information can be gathered directly from a Building Information Model (BIM). It is believed that this combination of BIM and GD for HVAC will lead to a more integrated and more efficient building design process.

4 CASE STUDY

A Matlab program was developed to address the first stage of the GD for HVAC process, generating zoning strategies for a given floor plan. This development also included the use of peak load calculations to determine the maximum cooling and heating loads, and the corresponding VAV box sizes. The

Canal Building, located on Carleton University Campus, was utilized as a test subject for this development.

All of the required parameter information regarding the rooms located on the third floor were gathered from a BIM Revit file and the infiltration rate for the entire building was received through a model calibration. The weather data was retrieved through a CWEC file for Ottawa that was found online [9]. The information regarding the building parameters are listed in Table 1 and were manually inserted into the Matlab code, the weather information that the code determined based on the data from the CWEC file is listed in Table 2. Typical values associated with the building parameters are listed in Table 1, non-typical values are listed as "Varies". For example, the windows in the Canal building have a U-value of 3.194 W/m^{2}K, but the window area varies based on the room.

Building Parameters	Values
Room Number	Varies
Room Type	Varies
Potential Occupants	Varies
Room Area (m^2)	Varies
Room Adjacency	Varies
Orientation (N,E,S,W)	Varies
Exterior Wall Area (m^2)	Varies
Window Area (m^2)	Varies
Window SHGC	0.655
Window U-Value (W/m^{2}K)	3.194
Floor to Floor Height (m)	4.2
Exterior Wall Resistance (m^{2}K/W)	4
Infiltration Rate (ACH)	0.2
Cooling Season Setpoint (°C)	23
Heating Season Setpoint (°C)	20

Table 1. Building Parameter Input

Weather Parameters	Values
Max Outdoor Temperature (°C)	33
Min Outdoor Temperature (°C)	-25

Table 2. Weather Data

A section called "User Defined Criteria" was added to allow the user to state preferences for the final design selection. This user defined criteria allows designers some flexibility when generating final design options. Three linearly weighted options influence the GA outcome and design optimization process: initial cost, energy efficiency, and occupant comfort. The weights range from 0 to 4, where a weight of zero indicates no importance, and a value of 4 indicates the highest importance.

Categories are assumed to influence the zoning strategy linearly. Occupant comfort is assumed to increase with the system efficiency, and the initial cost is inversely proportional to the mechanical efficiency. Of these assumptions, occupant comfort is a difficult parameter to quantify and will not generally be related linearly to the number of zones. Although ASHRAE has a recommended range of suitable values for occupant comfort to the number of zones, the specific value should ideally be based on individual occupant preference, which is almost never known prior to construction and can change over a buildings lifetime.

For this case study, user defined criteria was selected based on what is believed to be the current industry practice: a high importance for initial cost, and reduced consideration for system efficiency and occupant comfort. The selected case study values can be seen in Table 3.

Categories	User Defined Weighting
Importance of Initial Cost	3
Importance of System Efficiency	2
Importance of Occupant Comfort	1

Table 3. User Defined Criteria

The user defined criteria was selected in this manner to validate the functionality of the program, however, the intent is to allow for different design outcomes. Although zoning options were generated for the entire floor plan, only results for the five single occupant offices will be examined in this paper. Figure 8 displays these offices and Table 4 displays the zoning strategies that correspond to the user defined criteria.

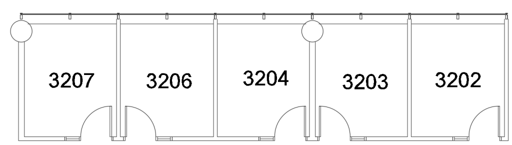

Figure 8. Third Floor Canal Building West Façade Single Occupant Offices

Strategy	Zone 1	Zone 2
1	3202 3203 3204 3206 3207	N/A
2	3202 3203	3204 3206 3207
3	3202 3203 3204	3206 3207

Table 4. West Façade Zoning Strategies

Mechanical design options were generated for the west façade offices based on the three zoning strategies listed in Table 4. Designs were generated using the same type of system that was constructed: a VAV based system with hydronic based radiant heating panels. VAV based systems are commonly selected in designs in order to *avoid over-cooling, most VAV systems are used in conjunction with separate heating systems* [ASHRAE 18.33], such as hydronic-based radiant panels. Table 5 represents the peak cooling load values determined for each of the zoning strategies.

Zoning Strategy	Zone 1 Peak Cooling Load (W)	Zone 2 Peak Cooling Load (W)
1	4,245	N/A
2	1,702	2,550
3	2,550	1,702

Table 5. West Zones Cooling Load Requirements

Zoning Strategy	VAV Supplier	Zone 1 VAV Size (mm)	Zone 2 VAV Size (mm)	Annual Supply & Return Fan Energy Consumption (GJ)	Annual Cooling Load (GJ)	Maximum Temperature (°C)	Days that the Room Temperature Exceeds Setpoint
1	Metalaire	250	N/A	3.31	4.44	23	0
1	Metalaire	200	N/A	1.96	4.43	24.68	5
1	Nailor	200	N/A	1.91	4.44	23	0
1	Nailor	175	N/A	1.28	4.44	24.28	3
2 & 3	*Metalaire*	*250*	*200*	*5.18*	*4.44*	*23*	*0*
2 & 3	Metalaire	200	200	3.78	4.44	23	0
2 & 3	Metalaire	200	150	2.96	4.44	23.59	1
2 & 3	Nailor	150	125	2.16	4.44	23	0
2 & 3	Nailor	125	100	1.67	4.43	25.01	7

Table 6. EnergyPlus Simulation Results

Since radiant panels are the source of heating for these offices, each room's peak heating load will be evaluated individually, rather than on a zone basis, as each room will contain its own radiant panel. These five offices have similar geometry and external wall details. This leads to a similar theoretical peak heating load, which was calculated to be 1,668W.

VAV boxes were selected that could supply the required amount of air to each zoning strategy found in Table 4. The required amount of air is the air flow rate required to meet the demands of the peak cooling loads found in Table 2, based on a cooling supply air temperature of 13 degrees celsius. Multiple supplier's VAV specifications were found online and incorporated into the code. Units from various suppliers are included; Metalaire, Nailor, Kreugar, E. H. Price, Titus, and Turtle Bailey. Once these VAV selections were generated, 38 EnergyPlus simulations were conducted to evaluate these VAV boxes, including the VAVs that were one size smaller. In addition, these VAV sizes were considered to evaluate the various trade-offs that may occur by under-sizing the unit. The setpoint may not be met during the entire cooling season, it may only occur once, which will save a substantial amount of the annual operational cost. Although BPS was performed for all of these suppliers, only the Metalaire and Nailor VAV results are presented in this paper. Results include the annual supply and return fan energy consumption, the five offices annual cooling load, days over the setpoint, and the magnitude of this temperature that were determined using EnergyPlus.

Table 6 represents the Metalaire and Nailor VAVs used in the EnergyPlus simulations. The Metalaire VAVs are analyzed to provide a comparison between the generated VAV results and the as-built design. The as-built design and results are located in the fifth row and are italicized. The Nailor VAV results were included since they yielded the most promising results for the various zoning strategies.

The third zoning option in Table 4, matches the strategy set in place. The VAV box selections that were based on the peak cooling load calculations were very promising, and the Metalaire VAV boxes were similar to those in the as-built, with the exception of one of the VAV boxes which was a unit smaller. The difference in VAV box sizing for the one unit is likely due to the fact that the hallway was grouped into this zone.

Ultimately, the identical zoning strategy and the similarity in the corresponding mechanical design is a strong indicator for the validity and functionality of the code. It confirms the code's capability to thermally zone offices, perform peak heating and cooling load calculations, and select the corresponding VAVs. The EnergyPlus simulations were performed to evaluate each design's fitness for this set of offices. It can be seen from the simulation results that the design that was implemented will always be capable of meeting the cooling demand, however, it yielded the most supply and return fan energy consumption out of the 38 options. VAV boxes operate under several damper positions which allows for specific volumes of air to pass through. VAV's are sized with minimum and maximum air flow through the VAV. Maximum air flow is sized to meet the peak load of a room, while the minimum flow relates to when the system is primarily providing ventilation or recirculation. Given that the system is only ever going to be dominated by the cooling demand for a maximum of 4 months of the year, this minimum air flow plays a significant role in the required supply and return fan energy. Since ASHRAE only requires 8.5 L/s/person (ASHRAE Std 62.1) it is advised to have low minimum air flow rate capabilities from the VAV, as can be seen in Table 6. Consider the same thermal zoning strategy as what was built, but instead utilizing Nailor VAVs. The cooling demand would have always met the cooling demand requirements, but due to significantly lower minimum airflow rate, this would have consumed 58.3% less fan energy in a year.

Instead of using the third zoning strategy, the first strategy could have been utilized. By pairing this strategy with a 200mm Nailor VAV, a decrease of 63.1% of the supply and return fan energy would have resulted. This design option would have been able to meet the cooling demands, but would have offered the occupants less control over their office temperatures, as 5 offices would have been grouped together. Furthermore, if this same zoning strategy was employed, but with a 175mm Nailor VAV, the energy consumption from the supply and return fans would have been 24.7% percent of what was constructed. This was the best solution from an energy consumption standpoint, but would have resulted in 3 days where the setpoint could not have been met. However, the resulting 3 under-cooled days would only have produced maximum temperatures of 24.28°C. Although this design is not ideal, the savings that correspond to this design make it a candidate worth considering. These high temperatures occur in the mid-afternoon, and if the occupants have flexible schedules, it might prove acceptable. These are typical considerations for a mechanical designer, however, due to time constraints, they are rarely able to perform sufficient calculations to arrive at these kinds of solutions. This type of development will allow designers the time to evaluate several design options, as opposed to only creating one design. As can be seen from this case study, utilization of this methodology could lead to substantial benefits, including lowering the energy consumption and operational cost.

5 FUTURE WORK

Pairing this development with an Architectural GD system is one of the first steps in the planned future work. Integration of HVAC generative design with Architectural generative design will further improve energy and system efficiency during the most flexible phase of design, the conceptual design phase. This coupling will also eliminate interferences between the two disciplines by shifting the industry standard from a collision detection mentality to an automated collision avoidance process. Mapping of the nodes, grid and adjacency lines, and the corresponding zone boundary lines should be completed, and integrated with an appropriate GA and fitness evaluator for supply diffusers and return grilles.

6 CONCLUSION

While the GD for HVAC code continues development, this research has demonstrated progress and improved capability. Zoning strategies were algorithmically generated and considered the type of room, as well as room adjacency, orientation, and load requirements. The code successfully integrated peak cooling and heating loads, and the corresponding VAV size for each zone into the GD process. When given the same trade-offs and evaluation criteria as those used in an existing building design, the system nearly replicates the existing zone level design. Furthermore, the system produced new design options for consideration, allowing a better understanding of the design space for the end user. By changing evaluation criteria, and considering the shift in design priorities due to new economical challenges, many more alternative designs can be easily generated and evaluated, improving design outcomes.

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