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Synthesis of Optimum HVAC System Configurations
by Evolutionary Algorithm

By

Yi Zhang

Submitted in partial fulfilment of the requirements for
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at
Loughborough University
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Abstract

The HVAC system configuration is a conceptual design of the HVAC system, including the employed components, the topology of the airflow network, and the control strategy with set points. Selection of HVAC system configuration is normally done in the early stage of the design process. The configuration design, however, has significant impacts on the performance of the final system. This thesis describes the development of the design synthesis of optimal HVAC system configurations by Evolutionary Algorithm.

In this research, the HVAC system configuration design synthesis has been formulated as an optimisation problem, in which, the component set of the configuration, the topology of the airflow network, and the control set points for the assumed supervisory control strategy, are the optimisation variables. Psychrometrics-based configuration model has been developed in order to evaluate the optimisation objective of minimising the annual energy consumption of the HVAC system. The optimisation is also subjected to a number of design constraints, including the connectivity of the topology, the performance limitations of the components, and the design requirements for the air-conditioned zones.

The configuration synthesis problem is a multi-level optimisation problem. The topology depends on the set of selected components, whereas the search space of the control set points changes with the different components and topology. On the other hand, the performance of the configuration is assessed with its optimum operation; therefore the control set points have to be optimised for each configuration solution, before the optimum configuration can be identified. In this research, a simultaneous evolutionary approach has been developed. All optimisation variables of the configuration have been encoded into an integrated genotypic data structure. Evolutionary operators have also been developed to search the topological space (for the optimum topology) and parametric space (for the optimal control set points) at the same time.

The performance of the developed approach has been validated with example optimisation problems. It is concluded that the implemented evolutionary algorithm has been able to find (near) optimum solutions for various design problems, though multiple trials may be required. The limitations of this approach and the direction of future development have been discussed.

Keywords: HVAC system configuration, design synthesis, optimisation, Evolutionary Algorithms, problem-specific operator, ageing operator
Acknowledgement

I would first like to acknowledge the financial support of ASHRAE through the research project RP1049. Very luckily I have had two supervisors during the work leading to this thesis. Dr Plamen Angelov, who initiated the idea of “design synthesis by optimisation” in the first place, had been the source of inspiration to me when I started working on this research project. Dr Jon Wright, whose enthusiasm, guidance and critical discussion has formed the final outcome of this research, gave me most of the help and support during my study. He owns my full-hearted gratitude.

I would especially like to thank Professor Vic Hanby, for the understanding and support that I had and I still do from him. I would like to give my special thanks to Dr Richard Buswell, who has kindly read part of this thesis, and given me invaluable advices.

This work, or any of my previous degrees, would not have been completed if it was not for the unending support of my parents. And to Zhen, my wife, and Xinbai, my little boy, I might never know how to express my love and grateful heart, though I will keep trying, in the rest of my life.

*** ***

I am now sitting here doing the final corrections, thinking of how after these five long years, this work is finally ready for printing and binding. My heart is so light that it makes me want to scream and hug everyone I know. I realize I would not have been able to say “job done!” if without two persons. Professor Jeff Spitler and Dr Chris Hinde have kindly taken the posts as my examiners, and gave me the most enjoyable and fruitful viva. Their comments and suggestions of correction have significantly improved the quality of the final thesis.
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Chapter 1

Introduction

DESIGN is "a rational, logical, sequential process intended to solve problems." [Web00]
Like that of other engineering systems, the design of Heating, Ventilation, and Air-Conditioning (HVAC) Systems for Buildings is a problem-solving and decision making process. It can be divided into four sequential phases by the level of detail:

Conceptual design – General HVAC system selection based on requirements identification and preliminary load calculation

Preliminary design – Schematic design of the HVAC system with preliminary component sizing

Detailed design – Detailed load calculation, ductwork and pipe-work layout, detailed component sizing, and design of control system

Engineering design – Fully detailed layout drawing in co-ordination with architectural and other services layout for engineering
Figure 1-1 depicts the impact of decisions on the design of a HVAC system diminishes with the progress of each design phase. Conversely, the cost of modification of earlier decisions increases sharply. Making appropriate decisions in the early stages of design is critical to the overall success of a project, as summarised by Al-Homoud; “careful long-term decisions in the design and operation of buildings can significantly improve their thermal performance and thus reduce their consumption of energy. Design decisions made during earlier phases of the design process cost less and have a more significant impact on the performance of the building.” [Al00]

![Diagram of Decision Costs and Impact on HVAC System Performance](image)

**Figure 1-1 Decision costs and their impact on the performance of HVAC system design stages**

One of the most important tasks in the early stages of HVAC system design is to determine the appropriate HVAC system configuration. The configuration of HVAC system includes the decision of system type, the selection of components and the choice of control strategies. For almost every HVAC system design project, there is more than one alternative configuration that would meet the design requirement. The question is: how to identify the possible alternatives and make the correct choice?

### 1.1 HVAC System Configuration

In general, the HVAC Systems are mechanical systems providing artificial environment for either operational requirement, or health and comfort of the occupants. An HVAC system comprises a number of components. The components are connected in certain configurations that allow thermal energy to be transported and air to be conditioned and distributed. Over the last century, many types of HVAC plant and system configuration have been
developed. The ASHRAE handbook [ASH96] lists typical HVAC system configurations (see Appendix A). These include configurations with different zoning (single-zoned and multiple-zoned), different media (all-air systems, air-water systems, and all-water systems), different component arrangements (centralized systems, fan-coil systems, dedicated fresh air systems, and unitary systems), different air transportation (single-duct, dual-duct, and multiple-deck systems), and different operation strategies (constant-air-volume and variable-air-volume systems). However, the list does not include configurations utilising components for heat recovery, evaporative cooling, and desiccant-based dehumidification. This class of configuration is becoming increasingly popular owing to the energy saving potential. There are also novel HVAC configurations being developed for particular applications, such as for office buildings and laboratories [Cui03, Son04].

In the early stage of system design, a designer is expected to select an appropriate HVAC configuration for certain design context. The configuration has to match the characteristics of the building, its usage and occupancy, and the climate in which it is situated. The configuration also has to make use of the available resources, and eventually fulfil the requirements of the design. The designer would also have the objectives such as delivering high quality indoor environment with minimum cost and environmental impact. The first step of choosing a configuration for an HVAC design, however, is to identify the alternative solutions. The alternatives can then be evaluated and improved; and consequently the best solution that suits the design requirements will be chosen. As the final choice is only made among the identified alternative solutions, the strategy of identifying alternatives becomes dominantly important.

In practice, the most commonly used approach in identifying alternative solutions for a design task, is based on “knowledge”. The knowledge may come from the designer’s own experiences, or the expertise of a group of practitioners; the knowledge may be in the form of memory, sketches, and text in books, or in the form of computerized rules and programs. Case-Based Reasoning (CBR) systems and Knowledge-Based Systems (KBS) have has achieved recognition in the field of HVAC design [Hal89, Mah97] and adopted in various applications [Faz89, Ros92,Sha94, Gar99]. The knowledge-based approach, however, has one major limitation – the limit of “knowledge”.

Knowledge-based approaches are limited by the volume of knowledge that has been collected and represented. Maintaining good coverage of the knowledge in the field of practice is difficult, especially when innovative designs and ideas are emerging all the time. An
alternative way to achieve optimal design is "automatic design synthesis", an optimisation approach that searches for the optimum among all possible solutions.

1.2 Synthesis of optimum design

Optimisation has three elements, (1) identified solution space, (2) means to evaluate each individual solution within the space, and (3) mathematical algorithm(s) to guide the search. A correctly implemented optimisation method is able to find the optimum or near-optimum solution. If the design of HVAC system configuration can be formulated as an optimisation problem, and an appropriate search method can be developed, it is possible to automatically "synthesize" (near-) optimum configuration for applications.

Optimisation methods have been used in the design of insulation, ductwork and hydraulic systems, component design, optimum control, and plant sizing. Typically, optimisation is performed on the detailed design to establish optimum parameter values for a given system. One such example is control optimisation where the problem is find optimal parameters and set points of a particular controller or control strategy for a given system. The solution space in this case, is the set of possible values of the parameters and set points. Wright gave an example of air-conditioning system sizing problem [Wri96]. Both the dimensions and mechanical structures of the coils and the fan, and the control set points such as water flow rate and fan speed, were taken as problem variables. It is a more complex problem compared to control optimisation, in that static structural parameters are considered at the same time as the control parameters. The values of the two classes of variables are interfering, such that a larger coil may need a set of completely different values for the control set points to achieve optimal operation. However, the solution space of the sizing problem is still defined by the value space of the parameters (including structural parameters and control set points). As the configuration of the air-conditioning system has been defined, the solution space remains static throughout the optimisation.

The main difference of the configuration problem to the sizing problem is that the configuration of the HVAC system is not pre-defined, but part of the solution variables to be searched. Once the configuration is chosen, the usual sizing variables associated to the particular configuration can be identified and searched. As a result, the configuration problem is a multi-level optimisation problem, in which the solution space for a lower-level sub-problem is determined by the part-solution on the upper-level, therefore “dynamic” during the optimisation. To be more specific, configuration of HVAC system is a schematic design
that contains a number of components and the arrangement of these components. The arrangement includes the linkage between the components, the supply of external sources, and the assumed control strategy. Each of the components in the system has a number of structural parameters and controllable variables. For the configurations that have different set or arrangement of components, the collection of the parameters and variables may be different. As a result, each configuration has a unique parametric solution space. Meanwhile, the quality of a configuration design is evaluated by its optimum performance, which means solving the sizing problem for the particular configuration is required. The configuration optimisation problem and its sizing problem are nested as illustrated in Figure 1-2.

Figure 1-2 Relation between configuration problem and sizing problem

The multi-level characteristic is the common feature for the so-called “system-level” design optimisation. In general, two different approaches exist for solving multi-level problems. They are the “iterative” approach and the “simultaneous” approach. The iterative approach treats each level of problem respectively, with a dedicated search method. The overall design problem is solved by nested optimisation loops. A higher level optimisation loop sets up and starts the optimisation on the lower level, whenever evaluation of a solution is required. The higher level loop has also to wait for the lower level loop to return, before proceeding to the next step.

The advantage of the iterative approach is that the optimisation algorithms used at each level of the optimisation can be selected and tuned to match the characteristics of the particular sub-optimisation problem. As a result, for each sub-problem, better performance in
terms of rate of convergence and robustness in finding an optimum solution can be achieved. However, overall progress of the iterative process is likely to be slow if the higher level problem is difficult to solve. Assuming that in average N evaluations have to be performed to optimize the parameters for one configuration, and M configurations must be searched to achieve a near-optimum solution, the total number of evaluations is N by M. As the complexity (M) of the higher level problem increases, the increase of the overall computational cost is magnified by N times. Therefore the iterative approach is more suitable for the problems where N and M are both "small". The configuration problem, on the contrary, is a hard problem with large search space. This will be further discussed in later chapters.

The simultaneous approach uses a unified optimisation process to search in both configuration space and parameter space at the same time. Considering that the global optimal solution is a pair of perfectly matched sub-solutions in both spaces, parallel searches in both spaces to find the match make sense. The benefit of the simultaneous search is that progress in the two spaces may complement each other; therefore results can be achieved quicker than the searches performed in each space separately. Proof and further explanations of this benefit will be given in the later chapters. However, as the solution space for the sizing problem is dependant on the solutions in configuration space, methods have to be developed to either weaken the association between the two spaces, or coordinate the progress. Special encoding methods and optimisation algorithm have been developed in this research to tackle these issues.

In brief, optimisation methods can be used to solve HVAC system configuration problem. However, as the configuration design is characterized as a multi-level problem, the main target of this research is to develop a simultaneous approach that optimizes the configuration and its parameters at the same time. In order to do this, a problem-specific encoding method and search algorithm have to be developed.

### 1.3 Alms and objectives

The objective of the research is to validate the concept of automatic configuration synthesis by establishing a method of configuration optimisation for HVAC system design. The aims of the work are:

- to review the application of optimisation in the field of HVAC system design and operation; to investigate approaches to system-level optimisation in other engineering disci-
plines; and to identify suitable optimisation algorithms for solving configuration problems (Chapter 2);

- to define the concept of configuration for HVAC systems; to analyse the impacts of configuration design on the energy performance; and to identify the theoretical requirements for an optimal HVAC system configuration (Chapter 3);

- to establish the optimisation problem for configuration synthesis, including, to develop configuration models for evaluation, to identify optimisation variables for the configuration synthesis problem, to define the optimisation objective and constraints, and to discuss the characteristics of the problem. (Chapter 4);

- to develop the encoding method for configuration synthesis problem; to realize the Evolutionary Algorithm (EA) as the optimisation method for configuration synthesis (Chapter 5);

- to develop the problem-specific methods (operators) for the optimisation algorithm; (Chapter 6);

- to validate the optimisation approach for HVAC system configuration synthesis, with two example optimisations, in which the first example demonstrates the ability of the approach in exploring the search space, whereas the second example validates the algorithm's ability in optimising the topology and the system operations simultaneously. (Chapter 7);

- to evaluate and analyse the performance of the developed approach with a more demanding task; also to provide further insight into the configuration optimisation problem (Chapter 8);

- to summarise the research, draw conclusions and provide directions for future research. (Chapter 9);
Chapter 2

Literature Review

Optimisation techniques have been extensively studied and practised on HVAC design problems. The synthesis of optimal system configuration, however, is a new concept. This chapter reviews the optimisation problems in the field of HVAC system design, and similar configuration problems for other engineering design. Evolutionary algorithms (EAs) are introduced; and the applications of EAs are discussed.

2.1 HVAC design optimisation

HVAC design optimisation problems can be categorized into two classes, as indicated by Dickinson and Bradshaw [Dic95]. The first class is optimisation of static design parameters; the second class is optimisation of the dynamic input variables, which usually include control scheduling and set points.

The static variables are the design parameters that are fixed in each simulation once chosen by the search algorithm. This type of problem usually includes the design of building envelopes, building system plant and components, ductwork and hydraulic systems, lighting
and zoning, and so forth. Al-homoud used direct search methods in optimising the thermal design of building envelopes [Al94]. Criteria and parameters of thermal design optimization for residential buildings [Al97a] and office buildings [Al97b] are further studied. His research showed that, comparing to the code-compliant base cases, significant energy savings can be achieved through optimization.

The use of genetic algorithms (GA) in optimizing the HVAC duct system design was reported by Asiedu et al. [Asi00]. The objective of their optimization was to minimize the life-cycle cost of duct work design, which includes materials and sizes of each section of the ducts. The duct system design is also subject to pressure balance and size limitation criteria. The available material and size of duct sections are encoded into integers, therefore GA works on the integer chromosome to search for the best combination. The results of their examples showed that with optimization, up to 13% saving in life-cycle is achievable comparing to the standard solution. Another application of GA in optimizing flow networks was reported by Qin et al. [Qin01]. The optimization of hydraulic conditions in district heating networks is represented as a maximum-minimum problem with non-linear constraints. GA is used to search for optimal locations and adjustments of valves in the network, in order to achieve hydraulic balance and minimize pumping energy. A number of successful applications of their approach have also been reported.

Nielsen took the interaction between building design and HVAC system into consideration [Nie02]. He used optimisation techniques (simulated annealing) in searching for optimal combination of building envelopes (wall, ceiling, floor, internal wall, and window frames), glazing, shading, lighting, and the HVAC system. In his research, the thermal properties of the envelopes have been carefully examined. However, the optimisation of building systems was simplified to choosing from a number of pre-defined configurations. Empirical data were used to evaluate the performance of the HVAC configurations, instead of simulation. As a result, it is best categorized as static design optimisation.

The control and scheduling optimisation differs to the static design optimisation, in that the problem variables (normally scheduled set points) are varying during each simulation. Each set point is a time series of variables whose values are to be optimised for the period of operation. This often results in larger number of problem variables comparing to those for design problems. House and Smith [Hou95] proposed a system approach to optimal control for building systems. A sequential quadratic programming (SQP) method is used to compute the optimal values of the discretized control set points for a 24-hour period. The optimal
control responses obtained using the approach compared favourably to a conventional control approach, with less energy use and more comfortable conditions.

Gibson [Gib97] described a personal-computer-based supervisory controller that works with a building energy management system (BEMS) to optimise cooling component operation. The dynamic behaviour of the building and the energy component was modelled with an artificial neural network (ANN). Genetic Algorithm was used to optimise the control schedule to fulfil the cooling requirement, as well as minimise electricity cost. Similar works have been reported by Dickinson and Bradshaw [Dic95], where they used genetic algorithm in optimal scheduling for building heating systems.

The combination of static design parameter optimisation, and the control scheduling problem, is the “sizing” problem. Von Thun and Witte [Thu91] proposed an optimisation-based design approach to tackle the problem of over-sized components as a result of conventional design procedure. The potentials of optimisation in three parts of building system were discussed. These include building envelope, room temperature scheduling, and air-handling system and components. It is envisaged that building and system types, duct and component sizes, and control strategy and scheduling of the HVAC system, are crucial to performance, therefore have to be optimised together to achieve the optimum design.

Wright [Wri96] studied component-sizing problems using genetic algorithms. He demonstrated optimisation of an example system, which has variables from both the physical dimensions of the components, and the operating points as represented by the controller set points. The optimisation method was adopted to find the combination of the design variables that gives the minimum system life-cycle cost. He indicated that the characteristics of sizing problems are having mixed continuous and discrete variables, and nonlinear constraints. Also the good solutions are often lying on the constraint boundaries. This, as a result, stresses the performance of optimisation algorithms, and requires mechanism for constraint handling. He studied the behaviour of genetic algorithm; and in later publications, proposed an effective constraint handling strategy for this class of problems [Far03].

Loosemore expanded the sizing problem to include building fabrics [Loo03]. It is argued that the building fabric, the design of the plant, and the control strategies, are interdependent factors that determine the performance of the building system. Optimising these factors in isolation to one another, as being done by most of the researchers, would not achieve the global optimum. However, the concept of “whole building optimisation” involves a large number of problem variables, which include both plant sizing variables, and
control scheduling variables. A method was developed to breakdown the problem into parallel targets (split fitness), each of which is determined by a segment of search space. As a result, the overall problem was divided into smaller optimisation problems that can be solved simultaneously. Significant performance advances in optimisation using this method have been concluded.

It is more difficult to segment the configuration problem for the HVAC system, and solve the sub-problems simultaneously. Consider the design process of building system, the natural steps are define the building (fabric) → choose an HVAC configuration → size the plant → schedule the control. The configuration problem is more tightly coupled with the sizing and the scheduling problems, because configuration defines the topology of search space of its fellow problems. Two different HVAC configurations may require completely different sets of sizing variables and scheduling variables, therefore, essentially, demand different sizing and scheduling problems to be solved. The configuration problem can be categorized as a multi-level problem, or system-level problem, because of its hierarchical structure. On the upper level, it is a combinatorial and graph-based structural problem; on the lower level, it is one or more parametric problem(s) whose definitions are dependent to the solution for the structural problem. These characteristics impose great challenges to solve the configuration problem using an optimisation algorithm.

2.2 Configuration problems and system-level synthesis

The configuration problem for HVAC system design is a multi-level problem that contains both structural and parametric optimisations. Although little work has been done to synthesise the configuration of HVAC systems, similar problems can be found in other engineering fields. Optimal synthesis of electronic circuit design and neural networks are closely analogous to the problem with HVAC configuration design. Firstly, the structural design of electronic circuits and neural networks involves topology synthesis for the networks. Secondly, the electronic components in the circuits, as well as the neurons in the neural networks, have parameters that have to be optimised in order to achieve optimal performance.

The HVAC configuration problem has similar structure to an analogue circuit or an artificial neural network. A configuration comprises a number of components, which are connected in an airflow network. The topology of how the components are connected is crucial to the performance of the configuration. Each component in the configuration is dedicated to
perform certain function of air-handling. The behaviour of each of the components is controlled by a number of parameters are associated to it. Apparently, a strong analogy exists between HVAC system configuration problems and the problems of analogue circuits and artificial neural networks. Advances of optimisation techniques developed in these fields are adaptable to HVAC configuration optimisation. The characteristics of the configuration problem for the HVAC systems are to be further discussed in Chapter 3. The advances in design synthesis of electronic circuits and artificial neural networks are reviewed here.

An artificial neural network (ANN) consists of a set of neurons, each of which performs a transfer function that processes the information passed to it. The neurons in the ANN are interconnected; and the underlying architecture of the ANN is a directed graph. Each connection in the graph can be assigned a weight. By designing the topological structure (design problem) and adjusting the weights (training problem), preferable performance of the ANN can be achieved. The design problem for ANN, or construction of topological structures, is regarded as a challenging task. Topological synthesis of ANN is normally formulated as a search problem, for which the solution space is discrete, and the objective surface is multimodal. The characteristics of the surface of the search space for artificial neural network structures [Yao99a] are summarized as: "infinitely large; discrete and discontinuous; complex and noisy; deceptive (similar topologies may have quite different performance); and multimodal (different topologies may have similar performance)." Global optimisation methods, such as evolutionary algorithms, are recommended for such problems.

The approach for evolving ANN architectures usually takes an iterative process. At first a number of candidate architectures are generated. Each of these candidates is trained in order to find the optimum set of weights. The fitness of the architecture is then calculated according to the training results. Based on their fitness, the "good" architectures are subsequently selected; and from which, new candidate solutions are synthesized. These steps are repeated until certain termination criteria are satisfied (e.g. objective achieved). Yao and Liu observed the limitation in the iterative approach [Yao97]. As the optimisation problem for connection weights is noisy and multimodal, a global optimum is not guaranteed from training. Consequently, using the results from training for fitness evaluation can be erroneous, and lead to sub-optimal architectures.

Simultaneous approach to evolve structure and weights of ANN at the same time is favoured in several researches. Yao and Liu incorporated a "partial training" strategy into the construction process. Unlike the "training" process in the iterative approach, the "partial training" is used as a means to explore weights, instead of calculating fitness of solution. As
a result, the weights are allowed to evolve along side the structures of ANN. He et al. [He02] described a method for constructing and training wavelet networks (a form of feed-forward ANN). A hierarchical genome was developed to encode both structure and weights in ANN. An evolutionary algorithm was then used to optimise structure and parameters simultaneously. In the approach described by Gao et al [Gao99], a matrix encoding for the feed-forward neural network is used. A group of matrices are used to encode the neural network solution. Each element of the matrices is the weight of a connection. The dimensions of the matrices imply the topology of the network. Special evolutionary operations have also been developed to be used with the matrix encoding. Edge-list encoding of the topology of ANN is adopted by Stanley and Miikkulainen [Sta02]. The genome contains two chromosomes: one represents the list of neurons in the network; the other lists the connections (edges). Weights of the connections are integrated in the edge-list. This encoding is capable of representing complex networks. However, special (and complicated) methods have to be developed to handle the evolution process effectively.

Evolutionary design approaches for electronic circuits have been reviewed by Yao and Higuchi [Yao99b]. The problem for electronic circuits design, especially for analogue circuits, is similar to that for ANNs. "The key issues are to find a suitable chromosome representation of the circuits," the authors summarized. Genetic Programming (GP) has been successfully applied to automatically synthesise human-competitive circuit designs [Koz00a, Koz00b, Koz03]. In the GP approach, trees are used to encode a set of programs that construct the actual circuit. This type of representation methods is also call indirect encoding. The use of direct encoding methods, such as Indexed Graph [Mil00a, Mil00b], has also been reported.

Applications of structural design optimisation methods, especially evolutionary approaches, can be found in many other engineering fields. More than 460 works were reviewed by Furman and Sahinidis [Fur02] in relation to the synthesis of heat exchanger networks (HEN). HEN convey thermal energy between a number of hot process streams and cold streams, for whose design, the topology, temperatures, and flow rates are critical for energy efficiency. A simulation-based design method for multi-objective batch plant design was presented by Bernal-Haro et al. [Ber02a, Ber02b]. A multi-objective batch plant is the production system that is capable of manufacturing several product families simultaneously. A batch plant contains a number of machineries, each of which can be described as a finite state automaton. The operation of these components can be scheduled to form flexible multiple production lines. The author adopted a two-stage approach to optimal batch plant
design. At the upper level, a genetic algorithm was used to generate structural solutions, which include components involved and their schedules and sizes; at the inner level, a discrete-event simulation model test and generate configuration details. A similar design problem for manufacturing systems has been reported by Pierreval and Tautou [Pie97].

Many design problems for engineering systems have multi-level structures, which can be solved in an iterative fashion. Li et al. used a multilevel genetic algorithm to solve the design problem of structural vibration control system [Li02]. The problem involved optimisation of (1) the number of active actuators, (2) the positions of the actuators, and (3) the control parameters for each of actuators. The authors implemented a three-level approach, in which genetic algorithms are nested into three loops: the uppermost level optimises the number of actuators, while the second and third levels optimise the positions and parameters for each of the solutions from first level, respectively. Observing the sub-problems are inter-related, efforts were made in coordinating the searches in each level. Another example of iterative approach to the multi-level optimisation is presented by Blickle, Teich, and Thiele [Bli98]. They tackle the system-level synthesis problem for heterogeneous hardware/software architecture design. Evolutionary algorithms have been used to explore the architecture design space (outer loop); meanwhile a scheduling heuristic has been employed to optimise the resource-constrained schedule of each candidate solution (inner loop). Fitness of the solutions are evaluated from both architecture, and scheduling result.

Alternatively, the multi-level structured optimisation problems can be represented in tree-type encoding, and solved simultaneously with problem-specific algorithms. Pierreval and Paris [Par01, Pie03] presented the configuration optimisation method for manufacturing systems. The configuration problem is encoded into a tree structure. In the root, there are the main design options and parameters; whereas in each level of branches, are the encoding of sub-options and sub-parameters. Evolutionary algorithms are used to optimise the tree representations. Special operators have been developed to ensure the effectiveness of search.

It can be concluded that the configuration (structural) design problems for many engineering systems, as well as that for HVAC systems, are multi-level in the nature. This type of problem can be solved either iteratively, using nested search algorithms, or simultaneously, using structured encoding and problem-specific algorithms. The choice of domain-specific representation of the problem, as well as the appropriate optimisation method, is the key to tackling the configuration synthesis problem.
2.3 Evolutionary algorithms

The configuration problem for HVAC system includes both structural (topological) parameters and dynamic (operational) variables. As for the operational parameters, such as control set points, the number of optimisation variables is large. Meanwhile, at the topology level of the optimisation, it is a graphic problem. As a combinatorial problem, it is expected to be hard to solve. To solve the configuration problem, an optimisation algorithm that can handle both the combinatorial problem, and the real problem with large variable space, is needed. A number of modern heuristic methods have been found effective in solving combinatorial and multimodal problems. Among others, there are Simulated Annealing [Met53, Kir83], Tabu Search [Glo86], Artificial Neural Networks [Hop85, Dur87, Gas89, Ila03], and Evolutionary Algorithms (EAs) [Hol75, Gol89, Koz92, Mic96]. The EAs have become one of the most successful and widely used algorithms.

![Evolutionary Algorithms Diagram](image)

Figure 2-1 General process of Evolutionary Algorithms

Evolutionary algorithms (EAs) are search methods that take their inspiration from natural selection and survival of the fittest in the biological world. EAs involve a search from a "population" of solutions, instead of from a single point. EAs also involve iterations of evaluation – selection – reproduction of the solutions. The solutions receive high "fitness" from evaluation are likely to survive, from competitive selection; and henceforth more likely
to produce new solutions using recombination and mutation mechanisms. Although the EAs belong to a class of stochastic approaches, the Evaluation – Selection – Reproduction loop ensures the search are guided towards regions of the space for which good solutions have been spotted. Figure 2-1 illustrates the general processes of EAs, as well as some techniques and strategies that are associated to each process.

The reproduction process usually contains two operations, recombination and mutation. The purpose of reproduction is to generate (interesting) new solutions from the existing solutions, by combination and modification. The choice of reproduction strategies is usually driven by the particulars of the problem, as well as the representation (encoding) of the problem. In fact, the design of problem encoding and the choice of reproduction strategy are two crucial aspects that identify different EAs flavours.

The Genetic Algorithm (GA) [Gol89] encodes problem variables into a binary string, in which, patterns of ‘0’ s and ‘1’ s (schemata) are believed to represent the features of a solution. By using generic reproduction operations that mix and modify the binary strings, the schemata representing “good” features, are preserved and accumulated; therefore the search leads to the optimal solution. One of the distinct characters of GA is that it is “neutral” to the problem. GA has been proved to be effective in solving both continuous and combinatorial problems. The drawbacks of binary encoding, however, are the computational overhead, and the difficulty in implementing problem-specific operators. As a result, real-encoded GAs that represent the problem in a real (or integer) string, have become increasingly popular.

Unlike GA, Evolutionary Programming (EP) [Fog66] and Evolutionary Strategy (ES) [Sch77] have been focused on real-encoded problems, instead of binary representation. This is because EP and ES place emphasis on the behavioural linkage between parent solutions and their offspring, rather than seeking to emulate specific genetic phenomena (crossover and mutation of genomes) as observed in nature. Though developed separately by two groups of researchers, the only major difference between EP and ES is that, while ES utilizes recombination operations, EP does not.

Genetic Programming (GP) [Koz92] was originally developed to evolve functions and programs. GP works on tree-type genotypic representations of the problem, in other word, programs that, when executed, represent the solution to that problem. GP utilizes recombination operations exchanging sub-trees between parent solutions, to produce new solutions; and uses mutation operation to modify sub-trees or overall architecture of the program. Compared to GA, in spite of the fact that GP works on tree-structures, rather than binary
strings, their methods and processes are very similar. Choosing GP usually depends on whether the optimisation problem can be represented in a tree-structure.

Although GA, GP, EP and ES were originally developed by different groups of researchers to tackle different optimisation problems, they share the common evolutionary process illustrated in Figure 2-1. They may differ from each other, on details such as those being annotated on the side of the main flowchart. Numerous EAs have been developed in recent years. It is becoming increasingly difficult to distinguish which flavour of EAs a particular implementation belongs. In this work, the umbrella term, Evolutionary Algorithm (EA), is used to describe the present approach.

2.4 Summary

This chapter reviewed the applications of optimisation techniques in the field of HVAC system design. The new concept of optimal configuration synthesis, though seen in other engineering design research, has not yet been investigated for HVAC systems. Compared to traditional optimisation problems for HVAC design, the configuration problem involves optimising the topological structure of the HVAC system. The combination of structural search and parametric search is a great challenge to the optimisation algorithms.

Design problems that contain both structural and parametric optimisations, have been presented in the fields of electronic circuits design, neural networks construction and training, and other engineering system designs. The common feature of this class of problems is that by their nature, the problems are multi-level. The parametric design variables are often associated to a particular structure of the system; therefore the search space can only be defined once the structural variables are identified. On the other hand, the evaluation of the structural variables depends on the optimality of the related parameters; which means the search of structural design can only proceed once the parameters are optimised to some extent.

There are two typical approaches to these multi-level problems, the iterative approach and the simultaneous approach. In the iterative approach, the structural problem and the parametric problem are optimized in two nested loops. In the outer loop, candidate structures are generated. The parameters of each candidate structure are subsequently optimised in the inner loop, in order to provide evaluation information for the solution. The simultaneous approach, however, optimizes the structure design and its parameters in one search. This
approach is favoured in the cases where the parametric optimisation problem is noisy and multi-modal, where the iterative approach is prone to producing sub-optimal results.

It can also be concluded from the literature review, that the choice of representation of the multi-level problem, and the design of optimisation algorithm, are important to solve the configuration problem. Evolutionary algorithms (EAs) have been one of the most successful modern heuristic methods. EAs have been successfully used in solving both structural and parametric problems. However, further development to the standard algorithms, and problem-specific customizations, are necessary. In the following chapters, the characteristics of the configuration problem for HVAC system design are studied. Special encoding of the problem and problem-specific evolutionary algorithm are to be developed and tested.
Chapter 3

Analysis of HVAC system configurations

The HVAC system is a mechanical system that "provides control of the internal environment to maintain specified conditions for a certain purpose." [Cha97] The configuration is the schematic design of the HVAC system. Selection of components, arrangement of air distribution, and strategy of operation, are elements of configuration design. A large HVAC system can be complex and involve many subsystems and components. The design of HVAC system is also driven by a number of different criteria, such as costs, energy consumption, indoor air quality, and thermal comfort. As the primary attempt to automatic synthesis of configurations, the scope of this research is limited to: (1) the configurations of secondary HVAC systems, and (2) the energy aspect of the configuration designs.

The secondary HVAC systems considered in this research contains only the components that are directly involved in the air-conditioning processes. This chapter describes how to represent an HVAC system configuration as a set of basic psychrometric processes (components) linked by airflow network (topology), and operated by a certain control strategy. Components, topology, and control strategy are identified as three elements of abstracted configuration design. The abstractions of some typical configurations are presented.
Theoretical analysis of the psychrometrics and energy balance in the secondary HVAC system is subsequently performed. A number of factors in configuration design that affect energy consumption of the system are identified. A conceptual optimal configuration design is derived from the analysis. The conceptual optimal configuration offers a benchmark for the design synthesis in the following chapters. At the end of this chapter, the scope and limitations of this research is summarized.

3.1 HVAC system configuration

The HVAC system considered in the present research is the secondary system, whose primary objective is to treat air to the preferred conditions and distribute it to the air-conditioned spaces. Figure 3-1 shows the configuration of dual-duct variable air volume (VAV) HVAC system with a single supply fan setup. The outside air is drawn into the system and mixed with return air. Then it passes through preheat coil, cooling coil, and humidifier in sequence. The supply air fan blows the air into two parallel main ducts. Each of the ducts is fitted with a reheat coil or a cooling coil to maintain a constant air temperature in the duct. In each conditioned zone, a dual duct VAV box is fitted to mix the air from the heating duct and the air from the cooling duct. The mixture is calculated to maintain the zone temperature. As the dual duct box is handling the variation of zone load by adjusting the volume of air drawn from the main ducts, the airflow volume in the system is varying. The speed of the supply air fan is controlled to maintain the static pressure in the main ducts.

Figure 3-1 Diagram of variable air volume, dual-duct, single-fan system [ASH96]

Figure 3-1 shows the dual-duct system that includes 2 heating coils, 2 cooling coils, 1 humidifier, 2 fans, dual duct boxes (essentially mixing boxes fitted with temperature-controlled dampers), diffusers, ductwork and fittings (splitters and mergers). Though not shown in the diagram, there are also dampers, sensors and controllers, and often, filters and silencer. Different HVAC systems can have different set of components, each of which has
different functionality and purpose. It will be difficult to synthesise an HVAC system design as it is in real life. Some abstraction and simplification are necessary.

Based on their purposes, the components of HVAC systems can be divided into four groups. The first group includes the air-handling components that actively change the property (or condition) of the air. The heating and cooling coils, humidifiers and dehumidifiers, and air filters are in this group. The second group of components relate to the distribution of air. These include fans, ducts, fittings, dampers, diffusers, mixing boxes, and inducers etc. The third group is operation-related. The types of components include sensors, controllers, and actuators. The last group of components are for miscellaneous functions, such as silencing. The components in the fourth group are excluded from this research, as they have normally little impact on energy performance of HVAC systems. For an HVAC system design, the arrangement of the first 3 groups of components defines its configuration, which consequently includes 3 aspects:

- The **air-handling components** — The presence of air-handling components tells what air-handling processes are involved in the configuration. The processes define how air is treated. It is possible to use the basic psychrometric processes to represent the vast varieties of air-handling components. This will be further discussed in 3.1.1.

- The **airflow network topology** — Fans, ductwork, fittings, dampers, and diffusers form the circulation network in which airflow is distributed from outside to the zones. The topology is the abstraction of the network that defines how the air-handling components in the system are connected to one another; hence determines how air is distributed and circulated. This will be discussed in 3.1.2.

- The **operation strategy** — The arrangement of sensors, controllers (control logics), and actuators determines the way how the system is operated, or "operation strategy". The typical operation strategies for HVAC systems include constant air volume (CAV), variable air volume (VAV), variable air volume and temperature (VVT), and supervisory optimal control etc. It is possible to investigate different control strategies without realizing the details of control components. That is, the control strategy can be represented as scheduling of a number of set points, thereby simplifying the configuration synthesis problem. This will be further discussed in 3.1.3.
3.1.1 Components

In building system simulation, "component" refers to the computer model of elementary part of HVAC systems [Han87]. In the present research, only air-handling components that are directly involved in psychrometric treatment of air are considered. The air filters, which are used to remove contaminants from air, are not considered due to irrelevance to thermal energy consumption. The airflow resistance that may be caused by the presence of filters in the system can be estimated as part of the ductwork.

Each air-handling component considered in this research can be represented as a basic process line on the psychrometric chart. Seven basic types of psychrometric processes are illustrated in Figure 3-2, where

1. Heating processes
2. Sensible cooling and cooling/dehumidifying processes
3. Evaporative cooling and direct injection humidifying processes
4. Supersaturated processes
5. Desiccant-based dehumidifying processes
6. Isothermal steam injection humidifying processes
7. Mixing and heat/enthalpy exchange processes

![Figure 3-2 Basic psychrometric process lines](image)

In order to simplify the problem, the types of components to be included in the configuration synthesis are limited to a minimal set. These components include heating coils, cooling coils, and steam injection humidifiers. Mixing (type 7 in Figure 3-2) is an important air-
conditioning process; therefore the mixing tees are included, too. The components are listed in Table 3-1. Also in the table, there are three components that cannot be represented as a line on the psychrometric chart. The diverging tees split a stream of air into two, without changing the condition of air. They are useful as the counterpart of mixing tees, in defining configuration topologies. The zones and the Outside air are 2 pseudo-components. Each zone represents a volume of air whose condition is controlled. The ambient environment is the source of outside air, and the sink for relief air from the system. The zones and the outside air components are required for topological representation of the configuration. This will be further discussed in the section 3.1.2.

<table>
<thead>
<tr>
<th>Type (Tag)</th>
<th>Type ID</th>
<th>Icon</th>
<th>Components</th>
<th>Psychrometric Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling coils (Cool)</td>
<td>3</td>
<td><img src="image" alt="Cooling coils Icon" /></td>
<td>Direct expansion coolers, cooling coils, etc.</td>
<td>2</td>
</tr>
<tr>
<td>Heating coils (Heat)</td>
<td>2</td>
<td><img src="image" alt="Heating coils Icon" /></td>
<td>Electric heaters, heating coils, and perimeter heaters, including radiators, fireplaces etc.</td>
<td>1</td>
</tr>
<tr>
<td>Steam injection humidifiers (Steam)</td>
<td>4</td>
<td><img src="image" alt="Steam injection humidifiers Icon" /></td>
<td>Isothermal steam injectors</td>
<td>6</td>
</tr>
<tr>
<td>Mixing tees (MIX)</td>
<td>1</td>
<td><img src="image" alt="Mixing tees Icon" /></td>
<td>Mixing tees, mixing boxes, plenums, inductors, etc.</td>
<td>7</td>
</tr>
<tr>
<td>Diverging tees (DIV)</td>
<td>0</td>
<td><img src="image" alt="Diverging tees Icon" /></td>
<td>Any equipment and location where airflow is split into 2 branches.</td>
<td>-</td>
</tr>
<tr>
<td>Zones (Zone)</td>
<td>7</td>
<td><img src="image" alt="Zones Icon" /></td>
<td>Conditioned air volume</td>
<td>-</td>
</tr>
<tr>
<td>Outside air (Ambient)</td>
<td>11</td>
<td><img src="image" alt="Outside air Icon" /></td>
<td>Ambient environment where fresh air is drawn and relief air is exhaust.</td>
<td>-</td>
</tr>
</tbody>
</table>
3.1.2 Topology

The system topology of a secondary HVAC system is the schematic abstraction of the arrangement and connectivity of its components. A system topology can be presented as a graph, in which, the components are presented as "nodes", whereas the airflows between components are presented as "edges". As airflows in the HVAC systems are normally directional, the system topology is a "directed graph" (or "digraph").

The topology of the dual-duct system in Figure 3-1 is shown in Figure 3-3. Note that the fans have been removed and the ambient and zone components have been added. The inclusion of Ambient and Zones makes the topology comprise only closed loops. Each and every component is connected in one or more cycles, in which air is circulated in the system. In Figure 3-3, “A” and “Z” represent Ambient and Zone, whereas “H”, “C”, “J” represents Heating coil, Cooling coil, and Steam injector, respectively. “’” indicates a diverging tee; and “O” is either a mixing tee or box. The dual-duct box at each terminal in Figure 3-1 has been simplified as a mixing box. Despite the various mechanisms used in different dual-duct boxes, their primary function is to control the mixture of air from the cool and heated ducts.

![Figure 3-3 Topology of the Dual-duct VAV system configuration](image)

There are 16 nodes and 20 edges in the graph. Note that each edge is a directed arrow, which means air can only flow in one direction from one component to another. This limitation is necessary for modelling topologies. In practice, however, a section of duct may allow air flowing in either direction in different operation modes. In such a case, two parallel edges with flow in opposite directions are needed to represent the connection. Most of the typical HVAC configurations can be represented as graphs of components and airflows, though approximations may be needed in some cases. Appendix A provides a list of configuration
topologies for the HVAC systems found in ASHRAE handbooks [ASH96]. Representation and approximation are explained in detail.

The underlying digraph for the topology of HVAC configuration has certain characteristics. First of all, as required for mass balance of airflows in the system, the digraph has to be "strongly connected". Strong connectivity of digraph is defined as below:

Let u and v be nodes in a digraph D. Then u and v are mutually reachable in D if D contains both a directed u→v walk and a directed v→u walk. Digraph D is strongly connected if every two nodes are mutually reachable in D.

Strong connectivity requirement means all components in the configuration are connected in the graph; also the airflow from any one component can be circulated to any other component, including itself. The structures in Figure 3-4 are infeasible because they violate the strong connectivity rule. In the topology (A), the airflow from the components on the right side of the cut line, cannot reach the components on the left side; whereas for topology (B), components on either side of the cut line cannot reach the other side. As a result, neither of the topologies in Figure 3-4 is considered feasible. There are further constraints to ensure that topologies are feasible. These constraints are defined in the next chapter.

![Figure 3-4 Topologies that are NOT strongly connected](image)

3.1.3 Operation strategy

The operation strategy for an HVAC system refers to the design of the control system that reacts to the change of circumstances to maintain specified operation targets. Even for the HVAC systems that have similar components and topology, the way they are operated

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1 A walk is an alternating sequence of vertices and edges, with each edge being incident to the vertices immediately preceding and succeeding it in the sequence.
may be very different. For example, the single-duct CAV system, the single-duct VAV system, and the single-zone fan-coil plus fresh air system (Appendix A, Figure A-1, A-4, and A-13) are similar in terms of topological design. In response to the change of zone load or ambient condition, the single-duct CAV system maintains the supply air volume, while controls the supply air temperature by resetting the reheating coil. The single-duct VAV system, however, adjusts the supply air volume to meet the zone load, by controlling the terminal dampers. As the pressure in the main duct is kept constant, reducing supply air volume means energy savings from the circulation fan. As for the fan-coil and fresh air system, the volume and parameters of fresh air supply are kept constant; whereas the fan-coil unit provides adjustment on both re-circulation of room air, and its parameters.

The operation strategy of an HVAC system has significant impact on its performance [Ard97]. Briefly, the traditional constant-air-volume (CAV) strategies are able to maintain the indoor conditions and air quality at the cost of excessive energy consumption. The variable air volume (VAV) systems show performance advantages in terms of energy efficiency, especially in part-load conditions. However, VAV systems may suffer from air quality problem during partial load conditions, due to low air supply volume. The variable air volume and temperature (VVT) strategy was developed to allow the partial air-conditioning load to be met by both air supply volume and temperature. However, the operation is locally controlled by predefined set points, instead of global optimum decisions. A better way of maintaining the target zone conditions is to control both the supply air volume and temperature based on the optimal supervisory control strategies.

A supervisory control strategy schedules the control set points globally and dynamically, based on the system model and the circumstances. Compared to CAV and VAV with local control, the simulation based supervisory control strategies have been proven to be able enhance energy performance of HVAC systems. With this prospect, the present research employs the supervisory control set points to describe the operation of the system. The virtual “supervisory controller” is implemented as an algorithm that optimises physical and operational features of the system in both design and realistic conditions.

- The operation strategy for the HVAC configurations is based on supervisory control.
- All parameters and variables in the system are available to the supervisory controller.
- The thermal and mass input of the air-handling components, and the air flow rates in the system, are controllable.
• The supervisory controller collects load and ambient conditions, and determines the optimal set points for the controllable components

In this way, the requirement for control system design as part of HVAC configuration synthesis is simplified to the optimisation of the set points for the operation in each design conditions.

3.2 Configuration analysis

The ability of an HVAC system to minimize system energy use depends on the system configuration and its operating strategy. In this context, the potential for system optimization is examined.

3.2.1 Choice of psychrometric processes and mixing

All HVAC system components have limits on their performance. The limitations appear in two forms; first, some HVAC system components have non-ideal psychrometric processes; and second, all HVAC components have a limited range of operation. There are 7 major types of psychrometric processes available for air conditioning (see Figure 3-2). As a single component is unlikely capable of handling all operation conditions, combination of different processes can be used to achieve certain temperature and humidity requirements. For HVAC system design, the possible combined processes are often numerous. Given the design criteria and circumstances, careful design of the processes gives the potential of energy saving.

Alternative processes

There are usually large numbers of alternative combinations of air-conditioning processes available for a specific HVAC design. For the examples in Figure 3-5, air in condition point A is to be treated to the temperature of 20°C, all the processes (1), (2), (3), and (4) are acceptable. The process (1) uses evaporative cooling, whereas the process (2) uses a dry cooling coil. Evaporative cooling is often energy efficient way to remove sensible heat. If dehumidification is also required, processes (3) and (4) are the options. The process (3) uses a cooling coil to remove excess moisture, and then reheat to achieve desired temperature. The requirement of a reheating is because dehumidification with cooling coil often results in over cooling, when the output of the cooling coil is controlled by the dew point. The process
(4) uses desiccant-based dehumidifier together with sensible cooling. In many applications the desiccant-based air-conditioning is proved to be more energy efficient.

![Figure 3-5 Choice of processes for cooling with/without dehumidification](image)

Although the evaporative cooling and desiccant-based dehumidification are not considered in this research, it is easy to include these types of components in the future development.

**Use of mixing**

The idea of mixing is to make best use of air at its present condition (e.g. zone condition and ambient condition), instead of processing it to the preferred conditions. Consider the operation of a cooling coil for example (see Figure 3-6). During summer operation, a cooling coil is used to cool and dehumidify the air to be supplied to the zones. Ideally, the cooling and dehumidifying process would cool the air from the ambient air condition (A) directly to the supply-air condition (B). However, in order to achieve the required supply air humidity ratio (B), it is necessary to overcool the air (B1'), with the result that the air must be reheated (B1' → B) before being supplied to the zone. The result is simultaneous cooling and heating in the system.

The alternative process (2) is to use mixing in the place of reheating. The air from condition point A is further cooled to condition B2', which is inline with supply condition B and zone condition C. Then the air at B2' is mixed with C at a ratio about 1:3, to achieve the
condition B. Providing the volume of supply air at condition B is the same as in process (1), the volume of air handled by the cooling coil is only ¼ comparing to that with reheating. This means savings in both cooling capacity and fan energy consumption. The principle in process (2) is that mixing should be used whenever it is possible to eliminate active heating, cooling, and humidification.

The principle of mixing is generally applicable, though subjects to many constraints in the real-world applications. For example, a cooling coil may not be able to cool the air to the condition $B_2'$, but somewhere between $B_2'$ and $B_1'$. In this case, reheating is still needed to heat the air to reach the extension line of $B \rightarrow C$, in order to mix with air at condition C. Only partial saving can be achieved in such circumstances.

**Free cooling and minimizing outside air load**

The idea of mixing is to make effective use of air at its present condition, instead of to treat it to the preferred conditions. The outside air is a good resource in certain conditions. Free cooling is an energy efficient way of meeting cooling load in the building, when the enthalpy of outside air is lower than that inside.

In winter and summer seasons, however, outside air load is often the major part of the total system load. In such cases, either heat recovery devices, or maximizing recirculation (in
order to minimize outside air intake), are preferable. As heat recovery devices are not included in this research, minimization of fresh air intake is considered as the only solution. From the energy balance point of view (see Figure 3-7), the outside air load is calculated by the enthalpy difference between fresh air and exhaust air multiplied by the fresh air mass flow rate. Therefore minimizing the enthalpy difference between fresh and exhaust air is also desired. The potential of the system in minimizing outside air load in operation is determined by the configuration, especially for multi-zoned systems. This will be further discussed in next section.

![Figure 3-7 Energy balance of HVAC system](image)

### 3.2.2 Multi-zone problems

The configuration design problems for multi-zone systems are more interesting than that for single zone system, because: (1) more zones means more design requirements to satisfy at the same time; (2) these requirements are often conflicting with each other, which results in a harder optimization problem; and (3) re-circulated zone air can be considered as a resource; therefore more possibilities of energy saving. In this section, the problems associated with multi-zone configurations are discussed.
Simultaneous cooling and heating

Simultaneous cooling and heating occurs in established HVAC systems for two reasons, due to the performance limits of HVAC components, and as a result of poor system configurations. Several established multi-zone system configurations are designed with zonal re-heat. Figure 3-8 (A) illustrates a typical single duct system with terminal re-heat to one zone. The operation of the cooling coil is determined by the requirement of Zone 1 in this case. As a result, fluctuations in Zone 2 have to be compensated by re-heating. The volume of air supplied to Zone 2 is unnecessarily cooled and consequently re-heated, which is apparently a waste of energy. The dual duct system in Figure 3-8 (B) can have the same problem if in any operation conditions the cooling coil and the heating coil are required to operate at the same time. Mixing of actively cooled and heated air in the system is also a waste of energy. Hence, it is expected that optimum system configurations would be such as to eliminate the need for zonal re-heat and associated wasted energy.

![Figure 3-8 Zonal Re-heat System and dual-duct system](image)

Distribution of fresh air

The outside air load is a function of the outside air flow rate and the enthalpy difference between the outside and exhaust air flows. Established HVAC system configurations (Appendix A), minimize the outside air load by restricting the outside air flow rate to that required to maintain the quality of the indoor air (other than at times of free-cooling). For multi-zone systems, however, the minimum fresh air intake is not always achievable for some configurations. The fresh air requirements and the cooling/heating demands are often in conflict for multi-zone systems; see Figure 3-9 for example.
Consider Zone 1 and Zone 2 have the same requirement for minimum fresh air supply ($\dot{M}_{a\text{ fresh}}$), whereas the cooling loads are different. The configuration can satisfy the cooling demands of both zones by adjusting the volume of cooled air supplied to each zone. Given the cooling demand of Zone 2 is twice as much as that of Zone 1, and the cooled air is supplied at the same temperature of $T_{sup}$, the mass flow rate to the Zone 2 has to be two times of that to the Zone 1 ($\dot{M}_{a2} = 2 \times \dot{M}_{a1}$). Suppose that Zone 2 is supplied with minimum fresh air ($\dot{M}_{a,\text{ fresh}}$), the amount of fresh air supplied to Zone 2 has to be $2 \times \dot{M}_{a,\text{ fresh}}$ in this case. In total, $3 \times \dot{M}_{a,\text{ fresh}}$ is drawn from ambient, instead of $2 \times \dot{M}_{a,\text{ fresh}}$ as the requirement, which means 50% extra outside air load.

Typical dual-duct systems have a similar problem, as the two zones are supplied from one main air stream. When conflict between fresh air supply and heating/cooling demands happens, energy efficiency has to be compromised. It is expected that the better multi-zone system configurations will have separate paths from the outside to each zone, to isolate fresh air demands on a zone-by-zone basis.

Conflicting demands for fresh air, sensible loads, and latent loads

The example in Figure 3-9 shows only the conflict between fresh air demands and sensible cooling demands of two zones. When latent loads are considered, the configurations are even more complicated to analysis. Other factors and requirements may add to the complexity of conflict, too, such as more zones, temperature and humidity ratio settings, air distribution, and so forth. An automatic tool to optimize the system configuration to meet conflicting demands with highest energy efficiency is desirable.
Inter-Zone Air Flow and load compensation

More energy savings are possible by carefully arranging the zones in the configuration. Each zone served by a multi-zone HVAC system has the potential to act as a heat source or heat sink (if constant conditions are maintained in each zone, then each zone is a “thermodynamic reservoir”). Provided that at least two zones are at different environmental conditions (temperature and humidity ratio), then the potential exists to offset the zone loads one against the other. This could be achieved using a heat pump, or more simply by the circulation of air between zones.

Figure 3-10 Load Reduction by Inter-Zone Air Flow

For example, Figure 3-10 A, illustrates two hypothetical zones, one of which is maintained at 20°C and the second at 25°C. Circulating air from the Zone1 (low temperature) to Zone2 (high temperature) will reduce the 10kW-cooling load for Zone2. Meanwhile the 10kW heating load in Zone1 can be offset by the air circulated from Zone2. If the temperature setting of Zone1 is higher than that of Zone2, however, circulating the air between Zone2 and Zone1 would only increase the loads for the zones. An economizer that recirculates the return air has the similar effect (Figure 3-10 B). Relief air from both zones are mixed and fed back to each zone. Since the returned air temperature is 22.5°C, the circulated
air volume required to offset the load in each zone is doubled, implying higher fan energy cost. Therefore, in the absence of a heat pump, it is expected that an optimum multi-zone system configuration would have some means of promoting inter-zone airflow.

Further possibility is to minimize the enthalpy difference between the fresh air and exhausted air, so as to reduce outside air load. Consider the two zones in Figure 3-11, which have different temperature settings. Exhausting from Zone2 (higher temperature) is more preferable to exhausting from Zone1. The potential of energy saving is marginal, though, because the intake volume of outside air should have been minimized.

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Figure 3-11 Minimizing enthalpy difference between fresh and relief air

3.2.3 Fan Energy Use

The energy used in mechanical ventilation is a function of the air flow rate and the flow resistance of the air handling components. The flow resistance is a function of the air flow rate, and the physical “size” and construction of the components. Hence, using an optimum control strategy to minimize the air flow rate, results in a reduction in fan energy consumption. Since the flow resistance is also a function of the physical “size” of the components (such as the fin density and depth of a cooling coil), and that the size of the components is dictated by the required capacity of the components, it would appear that there is limited scope for reduction of flow resistance, other than by using optimum control to minimize the air flow rate.

In most established system configurations (Appendix A), the air handling components are located in the supply air stream of the main duct. Since the supply air flow rate is the sum of the outside air and the re-circulated air flow rates, the supply air has the highest air flow rate in the system. Therefore, placing the air handling components in the supply air stream will
result in the highest fan energy use. The fan energy use could therefore be reduced by moving the air-handling components to the outside air, or recirculation air streams. The constraints on component performance (such as the practicable temperature difference across a cooling coil), are likely to dictate that the only viable alternative position would be to locate the air-handling components in the recirculation leg of the system. This has the added advantage that during periods of free cooling, the recirculation flow rate, and therefore flow resistance, is further reduced and would be zero for operating condition requiring 100% outside air. The saving made by placing the air-handling components (coils and humidifiers), in the recirculation leg depends on the relative reduction in recirculation flow rate compared to the supply air flow rate. Some energy savings may also be lost as simultaneous free and mechanical cooling would not be possible (a strategy derived from the enthalpy control of free-cooling).

3.2.4 Optimal configuration

From psychrometric and energy balance analysis of HVAC configurations, it can be concluded that improvement in energy efficiency can be achieved by realizing the following features:

- Providing independent air-handling plant for each zone; therefore avoiding conflicts in various demands between zones;

- Effective use of alternative psychrometric processes and mixing; avoiding simultaneous heating and cooling in all circumstances;

- Recirculation paths that allow inter-zone load compensation;

- While fulfilling minimum fresh air demands in all of zones, the volume of outside air is minimized;

- Enthalpy difference between outside air and exhaust air is minimized.

- The air-handling components are located out of the main air stream; therefore do not restrict airflow, especially when they are not employed.

Based on these criteria, a conceptual optimum configuration can be developed for the two-zone systems (Figure 3-12). The two zones are separately supplied with dedicated heating, cooling and humidifying components, and also inter-connected with two cross-zone
bypasses. This arrangement allows each zone being actively heated or cooled independently. The cross-zone passages enable inter-zone circulation for load compensation when available. By controlling the airflows in circulation and exhaust branches, relief air can be exhausted from either of the zones, to the environment; therefore minimizes outside air load. This configuration can be used as a performance benchmark for the optimisation of HVAC configurations. The operation of the conceptual optimum configuration will be further analyzed in Chapter 8.

![Diagram of the conceptual optimum two-zone configuration](image)

**Figure 3-12 The conceptual optimum two-zone configuration**

### 3.3 Research Approach

This chapter is intended to define the scope of HVAC system “configuration” to be synthesised. In this research, considerations are given to the secondary HVAC systems that condition and circulate air between ambient environment and the air-conditioned zones.

Briefly, a configuration of secondary HVAC system can be identified with three elements:

- The air-handling components involved in the system;
• Topology of airflow network, which defines how components are arranged and connected;

• The operation strategy of the system. Note that supervisory optimal control strategy has been selected for the configurations to be synthesised; however, the control set points for airflows and component duties need to be optimised.

Different aspects of HVAC configuration designs affect the energy efficiency of the system. By psychrometric and energy balance analysis, it is concluded that energy performance can be improved by realize certain design features. A conceptual optimal configuration has been developed for the 2-zone HVAC systems. This configuration, together with other typical HVAC configurations, will be used as performance benchmarks to validate the configuration synthesis approach.

The analysis above concluded that, firstly, HVAC system configuration can be represented using components, topology, and operation set points; secondly, the design of components, topology, operation set points, have significant impacts on the theoretical energy efficiency of the final system. It is suggested that, with an appropriate configuration model and a method to evaluate its energy performance, an optimisation algorithm can be applied to synthesise the optimal configuration. In summary, the approach adopted in this research is to develop the HVAC configuration model and the evaluation method, as well as the optimisation algorithm that is suitable for the configuration synthesis problem. This optimisation-based approach will be validated and evaluated with a number of design tasks. The optimality of the synthesised configurations is to be compared with established systems and the conceptual optimal configuration.
Chapter 4

The configuration optimisation problem

In Chapter 3, the potential impact of the HVAC system configuration design on the performance of the systems is discussed. Given the complexity of HVAC system configurations, it is impractical for a human designer to produce an “optimal” configuration that fulfils all the design requirements. An automatic design synthesiser is desired. As introduced in Chapter 1, the design process itself is an optimisation approach. It is possible to formulate the configuration synthesis problem as an optimisation problem, whose objective is to find the configuration with best performance.

This chapter discusses how to formulate the optimisation problem for the purpose of configuration synthesis for HVAC systems. The HVAC configuration model is discussed first. The model relies on psychrometrics and graph theory to simulation the operation of HVAC configuration. The formulation of the optimisation problem, including optimization variables, the objective function and the optimisation constraints, is discussed. Preliminary study of the landscape of the search space is also presented. The characteristics of the configuration synthesis problem indicate the requirement for a robust algorithm that can effectively handle combinatorial and multi-modal problems.
4.1 Configuration Modelling

The performance model for the HVAC configuration is the basis of evaluation and optimisation of the design. The purpose of the configuration model is to (1) validate operation and (2) evaluate energy consumption.

As discussed in Chapter 3, the main concern in this research is energy efficiency, therefore simplified psychrometric models are sufficient to evaluate the performance of configurations. A configuration model is comprised of component models and the topology. The topology of the configuration is realized by connecting the component models with airflows. In this section, the design of configuration model, realization of component models, and the graphical algorithms for solving the airflow and conditions in the system, are discussed.

4.1.1 Configuration model

The building blocks of configuration are software models for components listed in Chapter 3, Table 3-1. Each component model has a number of incoming and outgoing ports. Each port is linked either from, or to, an air flow object which encapsulates the properties of that air flow. The structure of the configuration model is illustrated in Figure 4-1.
In the example, 6 component models are linked together with 7 air flows. That means there are 7 air flow conditions to be determined in order to define the operation of the system. Among the 6 components, there are 3 "active" components that provide energy gain or loss to the system. There are also 2 airflows whose conditions are known. For the airflow that comes out of the Ambient component, the air condition is defined by weather data; for the air exiting the Zone, its condition must be the design condition. With this information, the operation of the system can be determined. The details of component models, and the algorithms solving the operation of a configuration, are discussed in the following sections.

4.1.2 Component models

In order to solve the psychrometrics of HVAC system configuration, the energy input to the system, the air flow rates in each branch, and the air conditions in each branch, have to be determined. The component models handle the energy consumption, psychrometrics, and balance of airflow. Each component model contains 3 processes as shown in Figure 4-2. The energy source converts heat and moisture input into comparable energy gain or loss in kilowatts. For example, a steam injector component that supplies 0.001 kg/s steam into the system is consuming 0.001 kg/s * 2454 kJ/kg = 2.454 kW of thermal energy, where 2454 kJ/kg is the evaporative heat of water at 20°C.

![Figure 4-2 HVAC system component model](image)

The psychrometric process model represents the change of air conditions on the psychrometric chart. Each component has a unique psychrometric process line. Psychrometric functions are used to calculate the relation between thermal input and air condition change. The airflow process model calculates air flow rate in each branch by the mass balance requirement of that the total input air mass flow equals to the total output air mass flow. The
airflow process also determines the proportion of fresh air in the output flows, as well as estimates pressure drop caused by the resistance to the airflow.

**Energy source model**

The energy source model reserves the possibility of modelling the primary energy efficiency. The possibility is to provide an efficiency factor that converts thermal input to the measure of primary resources, e.g. coal or crude oil. However, this is not concerned in the present research. The energy input to the component is measured by the actual enthalpy change in the air flow in kW. Table 4-1 listed the primary source required for each component, and their available range of capacities. Note that for a steam injector, the energy consumed is calculated by the heat required to evaporate the quantity of moisture at a temperature of 20°C.

<table>
<thead>
<tr>
<th>Component</th>
<th>Source variable</th>
<th>Range</th>
<th>Conversion factor</th>
<th>Energy consumption² (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat</td>
<td>Heat input in kW</td>
<td>[0, 20.0]</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Cool</td>
<td>Heat extraction in kW</td>
<td>[-20.0, 0]</td>
<td>-1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Steam</td>
<td>Steam input in kg/s</td>
<td>[0, 0.03]</td>
<td>2454.0³ (kW/kg/s)</td>
<td>2454.0</td>
</tr>
<tr>
<td>DIV</td>
<td>None</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>MIX</td>
<td>None</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Zone</td>
<td>None</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Ambient</td>
<td>None</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
</tbody>
</table>

**Psychrometric process model**

In this research, the air-handling components in the secondary HVAC systems include Heating Coil, Cooling Coil, and Steam Injection Humidifier. For Heating Coils and Cooling Coils, their duties are measured by heat flow (either as sources or sinks) as $Q_{\text{heat}}$ and $Q_{\text{cool}}$ (equation 4-1 and 4-2). For Steam Injection Humidifiers, the thermal duty $Q_{\text{humidifying}}$ is calculated by the latent heat of evaporation at temperature of 20 °C.

Total heating capacity (kW):

$$Q_{\text{heating}} = \sum_{i}^{HC} Q_{\text{hc}}$$  \hspace{1cm} (4-1)

² Example energy consumption values are calculated from source variable value of 1.0 multiplied by the Conversion factor.
³ Based on the evaporative heat of water at 20°C
Total cooling capacity (kW): \[ Q_{\text{cooling}} = \sum_{i}^{n} Q_{\text{coil}} \] (4-2)

Total humidifying capacity (kW): \[ Q_{\text{humidifying}} = \sum_{i}^{n} (2454.0 \times \dot{m}_{\text{steam}}) \] (4-3)

Heating coil (Heat)

The process line of heating with coil is a straight line on the psychrometric chart (A→B in Figure 4-3). Providing that temperature and humidity ratio of A are \( T_A \) and \( g_A \), heat input is \( Q_{\text{heating}} \), and air mass flow rate is \( \dot{M}_a \), the temperature and humidity ratio of B is calculated with the following equations using psychrometric functions:

\[ Q_{\text{heating}} = \dot{M}_a (h_B - h_A) \] (4-4)

\[ g_B = g_A \] (4-5)

![Figure 4-3 Process of heating](image)

Cooling coil (Cool)

For cooling, it is assumed no condensation occurs (dry coil) before the air temperature reaches dew point, and after that, the air condition stays saturated on the 100% relative humidity line. The process line of cooling with coil is illustrated in Figure 4-4, A→B′→B. The condition of B is calculated with the following equations:

\[ Q_{\text{cooling}} = \dot{M}_a (h_B - h_A) \] (4-6)
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\[
\begin{align*}
&g_B = g_A, \quad 0 \geq Q_{\text{cooling}} \geq M_a (h_B' - h_A) \\
&RH_B = 100\%, \quad Q_{\text{cooling}} < M_a (h_B' - h_A) < 0
\end{align*}
\]  
(4-7)

Humidifying by steam injection (Steam)

The process line of steam injection is a vertical straight line (isothermal line) on the psychrometric chart (A\(\rightarrow\)B in Figure 4-5). Steam is assumed to be injected at the temperature of 20°C, and sensible heat input to the air stream is ignored. Given the quantity of steam injected is \(S\), the condition of B is calculated with the following equations:

\[
S = \dot{M}_a (g_B - g_A)
\]  
(4-8)

\[
T_B = T_A
\]  
(4-9)

Figure 4-4 Process of cooling

Figure 4-5 Process of steam injection
Convergence of air streams (MIX)

The process of mixing two air stream A and C is illustrated in Figure 4-6, where condition of B is calculated by:

\[ T_B = \frac{\dot{M}_{aA} T_A + \dot{M}_{aC} T_C}{\dot{M}_{aA} + \dot{M}_{aC}} \]  \hspace{1cm} (4-10)

\[ g_B = \frac{\dot{M}_{aA} g_A + \dot{M}_{aC} g_C}{\dot{M}_{aA} + \dot{M}_{aC}} \]  \hspace{1cm} (4-11)

Figure 4-6 Process of mixing air

Zone gain and expected supply condition (Zone)

As mentioned before, the output of Zone is a constant condition determined by design requirement. Unlike the previous component models, the zone model is to calculate the preferred supply condition from its design condition (output to input). The supplied air is to offset the sensible and latent load of the zone; therefore the following equations are used:

\[ Q_s = \dot{M}_a C_p (T_Z - T_S) \]  \hspace{1cm} (4-12)

\[ Q_l = \dot{M}_a L (g_Z - g_S) \]  \hspace{1cm} (4-13)

Where, \( Q_s \) and \( Q_l \) are sensible and latent load respectively. \( L \) is the evaporative heat of water at 20°C.
Air flow model

Each component has also an air flow model to calculate flow balance and resistance. For the components that have one input and one output port, the flow balance is:

\[ \dot{M}_{ain} = \dot{M}_{aout} \]  \hspace{1cm} (4-14)

For a diverging tee (DIV), which has one input and two output ports:

\[ \dot{M}_{ain} = \dot{M}_{aout1} + \dot{M}_{aout2} \]  \hspace{1cm} (4-15)

For a mixing tee (MIX), which has two input and one output port:

\[ \dot{M}_{ain1} + \dot{M}_{ain2} = \dot{M}_{aout} \]  \hspace{1cm} (4-16)

Note that the flow balance assumes that the system is airtight, which is often not the case in practice.

The airflow static pressure loss model is used to evaluate fan energy consumption due to resistance to airflow. Due to the lack of Fan model in this research, the system simulation does not directly provide energy consumption information on fans. Instead, the energy consumed in circulating air in the HVAC system is estimated by the resistance to airflow and the mass flow rate.

\[ W_{fan} = \frac{\Delta P \cdot \dot{M}_{air}}{\rho_{air} \cdot \eta_{fan} \cdot \eta_{motor}} \text{[kW]} \]  \hspace{1cm} (4-17)
Where, total pressure loss in system (Pa),

$$\Delta P = \sum \left( K_{\text{comp}_i} \cdot \dot{M}_{\text{comp}_i}^2 \right) + K_{\text{duct}} \cdot \dot{M}_{\text{duct}}^2$$  \hspace{1cm} (4-18)

$K$ [Pa.s²/kg²] is the resistance factor of each component and the ductwork (see Table 4-2)

<table>
<thead>
<tr>
<th>Component</th>
<th>$K$ (Pa.s²/kg²)</th>
<th>Nominal Ma</th>
<th>Pressure Loss @ Ma=1.0kg/s (Pa)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diverging tee</td>
<td>26.00</td>
<td>input</td>
<td>26.00</td>
<td>Air splitter with dampers</td>
</tr>
<tr>
<td>Mixing tee</td>
<td>5.20</td>
<td>output</td>
<td>5.20</td>
<td>Air converger, no damper</td>
</tr>
<tr>
<td>Heating Coil</td>
<td>11.80</td>
<td>through</td>
<td>11.80</td>
<td>Coil with facing area 0.5 m²</td>
</tr>
<tr>
<td>Cooling Coil</td>
<td>11.80</td>
<td>through</td>
<td>11.80</td>
<td>Coil with facing area 0.5 m²</td>
</tr>
<tr>
<td>Steam injector</td>
<td>1.04</td>
<td>through</td>
<td>1.04</td>
<td>Steam injector with single nozzle</td>
</tr>
<tr>
<td>Zone</td>
<td>3.95</td>
<td>through</td>
<td>3.95</td>
<td>Distributor and exhaust grill</td>
</tr>
<tr>
<td>Ambient</td>
<td>7.80</td>
<td>through</td>
<td>7.80</td>
<td>Air inlet, damper, and air outlet</td>
</tr>
<tr>
<td>Ductwork</td>
<td>38.19</td>
<td>sum of zones</td>
<td>38.19</td>
<td>Ducts and fittings equivalent to 250m straight ducts</td>
</tr>
</tbody>
</table>

Total air mass flow rate in system (kg/s),

$$\dot{M}_{\text{air}} = \sum_{i} \dot{M}_{\text{zone}_i}$$  \hspace{1cm} (4-19)

$\rho_{\text{air}} = 1.191$  \hspace{1cm} Air density at 20°C and 50% (kg/m³)

$\eta_{\text{fan}} = 0.75$  \hspace{1cm} Efficiency of fan

$\eta_{\text{motor}} = 0.85$  \hspace{1cm} Efficiency of motor
Constraints on the component performance

A number of constraints are required to ensure the operation of components is physically feasible and realizable in practice (see Table 4-3). These constraints include:

Capacity – the maximum capacity of the energy input to each component is limited. For example, the present capacity limits are, 25kw for heating coils, - 50kw for cooling coils, and 0.02kg/s for steam injectors.

Flow rate – the maximum mass flow rate of air that a component can handle is limited to 3.0kg/s.

Temperature – minimum and maximum temperature of air that passes through a component is limited, to represent customized types and reality. For cooling coils, the minimum and maximum temperatures of air are set to 5°C and 100°C respectively. For steam injectors, the setting is 10°C and 100°C. For zones, the limits are defined as current temperature setting +/- maximum temperature difference at supply point (7.0°C at present). The limits for other components are -50°C to 100°C.

Condensation -- condensation of moisture happens when the temperature of air drops below the dew point. In some components, condensation is not allowed to occur. These components include diverging tees, heating coils, and zones.

Table 4-3 Further constraints on components

<table>
<thead>
<tr>
<th>Component</th>
<th>Range of air flow (kg/s) ([\dot{m}<em>{\text{min}}, \dot{m}</em>{\text{max}}])</th>
<th>Requirement of fresh air (kg/s) ([\dot{m}<em>{\text{fresh, min}}, \dot{m}</em>{\text{fresh, max}}])</th>
<th>Range of temperature ([T_{\text{min}}, T_{\text{max}}])</th>
<th>Allow condensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat</td>
<td>[0.0, 3.0]</td>
<td>[0.0, 3.0]</td>
<td>[-50.0, 100.0]</td>
<td>False</td>
</tr>
<tr>
<td>Cool</td>
<td>[0.0, 3.0]</td>
<td>[0.0, 3.0]</td>
<td>[5.0, 100.0]</td>
<td>True</td>
</tr>
<tr>
<td>Steam</td>
<td>[0.0, 3.0]</td>
<td>[0.0, 3.0]</td>
<td>[10.0, 100.0]</td>
<td>True</td>
</tr>
<tr>
<td>DIV</td>
<td>[0.0, 3.0]</td>
<td>[0.0, 3.0]</td>
<td>[-50.0, 100.0]</td>
<td>False</td>
</tr>
<tr>
<td>MIX</td>
<td>[0.0, 3.0]</td>
<td>[0.0, 3.0]</td>
<td>[-50.0, 100.0]</td>
<td>True</td>
</tr>
<tr>
<td>Zone</td>
<td>(design brief)</td>
<td>(design brief)</td>
<td>([T_{Z-7.0}, T_{Z+7.0}])</td>
<td>False</td>
</tr>
<tr>
<td>Ambient</td>
<td>[0.0, 3.0]</td>
<td>[0.0, 0.0]</td>
<td>[-50.0, 100.0]</td>
<td>True</td>
</tr>
</tbody>
</table>

* Acceptable supply temperature range is the zone temperature +/- 7.0 °C
4.1.3 Solution of air flow rates

Solving of airflow in the system configuration is based on graphical methods. Theoretically, in order to determine the air flow rates in all the branches in the network, only the air flows in a number of branches have to be assigned. The air flows in the rest of branches can be derived from the known branches. For the HVAC configuration application, the number of branches whose air flows have to be assigned is equal to the number of diverging or mixing sections plus one \((M+1)\).

\[
\text{Number of paths to be set} = \text{number of edges} - \text{number of nodes} + 1; \\
= \text{number of DIVs} + 1; \\
= \text{number of MIX's} + 1;
\]

The actual branches whose airflows have to be assigned are determined by a tree growing method. For the example in Figure 4-8, a node tree is grown from the root \((A)\). Obviously, when path 5 and 6 are determined, all other paths can be calculated subsequently. In this case, the air flow rates in path 5 and 6 are optimization variables. They are the first 2 genes in each FlowDuty chromosome to be optimized.

![Tree growing diagram](image)

**Figure 4-8 Determination of air flow rates in the configuration**

The node tree is grown from the graph using an iterative function. At first, a node in the graph is selected as the root node for the tree. In the case of HVAC configuration, the root node is normally the Ambient component. Start from the root node, the tree is grown with the iteration of the following function.
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<table>
<thead>
<tr>
<th>Function</th>
<th>growFromGraph (Providing the graph, the current node in the graph, and the current node in the tree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>For all nodes adjacent directionally to the current node in the graph, Do</td>
<td></td>
</tr>
<tr>
<td>Create a tree node from the graph node;</td>
<td></td>
</tr>
<tr>
<td>Attach the tree node to the current tree node as its leaf;</td>
<td></td>
</tr>
<tr>
<td>If The tree contains an identical node as the attached leaf, then</td>
<td></td>
</tr>
<tr>
<td>If all of the nodes in the graph have been processed, then</td>
<td></td>
</tr>
<tr>
<td>Returns DONE;</td>
<td></td>
</tr>
<tr>
<td>End if</td>
<td></td>
</tr>
<tr>
<td>Else</td>
<td></td>
</tr>
<tr>
<td>Iterative call to this function with the discovered node in the graph, and the last attached node in the tree;</td>
<td></td>
</tr>
<tr>
<td>If the call returns DONE, then Returns DONE;</td>
<td></td>
</tr>
<tr>
<td>End if</td>
<td></td>
</tr>
<tr>
<td>Next node</td>
<td></td>
</tr>
<tr>
<td>Returns CONTINUE;</td>
<td></td>
</tr>
<tr>
<td>End Function</td>
<td></td>
</tr>
</tbody>
</table>

List 4-1 Algorithm for tree-growing from directed graph

4.1.4 Solution of air conditions

In the present design of component model, the input air condition, the air flow rate in the component, and its heating, cooling, or humidifying duty have to be set before the output air condition can be calculated. The exceptions are the Ambient and Zone components. The output condition of Ambient component is from the weather data. The output air condition from the Zone is assumed to match its desired conditions; and this is guaranteed by design constraints. As a result, the output air conditions from Ambient and Zones can be used as start point in the solution of air conditions in the system.

The air flow rates in the system can be determined in the way described in the previous section. The heating, cooling, and humidifying duties associated to the air-handling components are optimisation variables whose value to be set by the search algorithm. Starting from the Ambient and the Zones, the solution sequence of the components can be derived from the topology. For the example in Figure 4-9, the output air condition of ambient component (A) and zone (Z) is independent to their inputs. Starting from (A), the output condition 1 can be calculated. However for component (1), the input condition 5 is yet unknown. From (Z), condition 4 can be calculated; therefore (3) can calculate condition 5 and 6; (1) can thus calculate 2 from 1 and 5; then (2) calculates 3; and system is solved.
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For an HVAC configuration, the solution order of its components is determined using the following method. First mark all the output air flows from the Ambient component and all the Zone components as known. Then repeat the following steps until all the components have been added to the sort (see List 4-2):

- Select a component whose input air flow(s) are all marked as known.
- Add the component to the sort.
- Mark all the output air flow(s) from it as known.
- Remove the component from the configuration.

**Function**  
\texttt{topologicalSort} (Providing the configuration topology)

1. Create an empty list for the sorted nodes;
2. Insert all "Ambient" and "Zone" components into the sorted list;
3. Select output air flows from "Ambient" and "Zone" components;
4. Mark the selected air flows as \texttt{KNOWN};
5. Remove the "Ambient" and "Zone" components from the topology;
6. Do:
   - Select a component whose input air flow(s) are all marked as \texttt{KNOWN};
   - Add the selected component to the sorted list;
   - Mark all the output air flow(s) from the component as \texttt{KNOWN};
   - Remove the component from the topology;
   - Until (the configuration topology is empty);
7. Returns (the sorted list);

**List 4-2 Algorithm for topological sort**

When the sorted list is achieved, solving the operation of the configuration is done by calling the psychrometric model for each component in the order according to the list. The sorted list ensures that all the required input air conditions are available for a component model to calculate its output.
It is worthwhile to remember that the topological sorting algorithm requires the graph to be "acyclic". The topologies of HVAC configurations are cyclic graphs. However, as the air conditions of Ambient and Zone components are known, they are served as cycle breakers in the topological sorting. This is also the reason that a feasible topology requires at least one Ambient or Zone component in each cycle.

4.1.5 The use of the configuration model

The configuration model is used to evaluate the potential performance of a configuration design. The configuration model is created from the design specification, which describes the set of components and how they are connected. Then the model is put under a number of operating conditions in order to simulate its operation throughout a year. In each operating condition, the following examinations are performed:

- Check feasibility of the operation of each and every component, and the configuration as whole;
- Evaluate the fulfilment of design requirements;
- Assess the energy consumption of the configuration;

The results of examination in all operating conditions are consequently summarized to provide an evaluation score of the configuration design. This procedure is formulated as an optimisation problem, which can be solved by suitable optimisation algorithms.

4.2 Configuration design optimisation

In general, an optimisation problem is "to minimize/maximize the objective(s) that are subjected to a number of qualitative and quantitative constraints". The optimization problem for the HVAC system design synthesis has been formulated as such the constraint-satisfying minimization problem in equation 4-20 ~ 4-22:

Minimize:

\[
J = f(X_{\text{comp}}, Y_{\text{topo}}, Z_{\text{damp}}) = \sum_{\text{comps}} \left( w_{\text{ Cond },j} \cdot \left( \sum_{\text{comps}} Q_{\text{ comp },j} + W_{\text{ fan }} \right) \right)
\]  (4-20)

Subject to:
\[ h_j(X_{comp}, Y_{topo}, Z_{duty}) = 0 \]  \hspace{1cm} (4-21)

\[ g_k(X_{comp}, Y_{topo}, Z_{duty}) \leq \varepsilon_k \]  \hspace{1cm} (4-22)

Where:

\( X_{comp} = (x_1, ..., x_n) \in \mathbb{Z}^n \) Integer variables representing the set of components of a configuration, in dimension of maximum \( n \) (components)

\( Y_{topo} = (y_1, ..., y_{n+m}) \in \mathbb{Z}^{n+m} \) Integer optimization variables representing the topology of a configuration, in dimension of \( n \) (components) + \( m \) (DIV5's)

\( Z_{duty} = (z_1, ..., z_{m+1+k}) \in \mathbb{R}^{m+1+k} \) Real optimization variables representing the operational duty setting includes airflow rates and coil duties in the system under a design condition, in dimension of \( m \) (DIVs) + 1 + \( k \) (active components)

\( W_{Cond} \) Weight of a design condition as the ratio of nominal occurrence (hours) of the condition in a typical year, to the total hours of the year

\( Q_{comp} \) The duty (kW) of a component in the design condition

\( W_{fan} \) Fan power (kW) for air circulation in the system in the design condition

\( h_j \) Qualitative constraints that ensure the correctness of a configuration design. These constraints include formulation of chromosomes, feasibility of topology, and feasibility of operations

\( g_k \) Constraints for the fulfillment of design requirements, such as zone temperature, humidity, and supply of fresh air

\(^5\) "DIV" is the tag for Diverging Tee; see page 23, Table 3-1.
The optimisation variables are also termed the decision variables or problem variables in the literature. For the configuration synthesis problem, the optimisation variables include three groups, the set of components \( (X_{\text{comp}}) \), the topology \( (Y_{\text{topo}}) \), and the operational parameters \( (Z_{\text{oper}}) \).

Components

The set of components to be present in the synthesised configuration are a list of components of different types. This is usually a subset of the component pool, which defines the maximum availability of components of each type.

An alternative approach is to select a "large" set of components before the optimisation, and freeze it. The optimisation process works on the fixed component set, and should be able to identify redundant components and move them to places where they have less impact on the system performance. A manual post process can remove the redundant components from the configuration after the synthesis. In this way, the component set is effectively optimised. This is the approach to be taken in this research.
Topology

The topology variables define the air flow network that connects all the components in the configuration. The air flow network determines how the air to be circulated, treated, and distributed in the system. This is the crucial part of the configuration design.

System operation

The operation variables that define the operation of the synthesised configuration in certain condition include air flow rates in the system, and duties of the components. For configuration design, a single operation condition is insufficient to ensure correct operation throughout the year. Multiple operation conditions have to be tested to confirm that correct operation is achievable for all working conditions. Therefore multiple sets of operation variables are required.

4.2.2 The objective function

In this research, the optimisation objective for HVAC system configuration is to minimise the annual energy consumption. A number of typical operation conditions in all four seasons are selected, in order to (1) validate the operation in all conditions, and (2) estimate annual energy consumption. Preferably, the typical conditions are chosen based on statistics of hourly weather and load data throughout the year. For each operating condition, the energy consumption is comprised of two parts, the duties on the air-handling components, and energy consumed by fans to circulate air. The annual energy consumption is estimated by multiplying the energy consumption at each operating condition by the occurrence ratio of the condition. (See Equation 4-23)

\[
Q_{\text{annual}} = \sum_{j=1}^{L} (w_j Q_j)
\]

\[
= \sum_{j=1}^{L} w_c \left[ \sum_{k=1}^{K} |Q_{j,k}| + W_{fan,j} \right] (kW) \tag{4-23}
\]

\[
= \sum_{j=1}^{L} w_c \left[ \sum_{k=1}^{K} |Q_{j,k}| + \frac{\sum_{n=1}^{N} R_{n} \dot{m}_{fan,j,n}^2 + R_{\text{dust} \dot{m}_{\text{supply},j}^2} \cdot \dot{m}_{\text{supply},j}}{\eta_{fan}} \right]
\]

Where,
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\( Q_{\text{annual}} \) - Annual average energy consumption in (kW)

\( Q_c \) - Energy consumption in each operation condition (kW)

\( w_c \) - Weight of each operation condition \( \sum_{c=1}^{J} w_c = 1 \)

\( J \) - Number of operation conditions

\( Q_{c,i} \) - Thermal input (capacity) of each air-handling component (kW), see Table 4-1

\( K \) - Number of air handling components in the configuration

\( W_{c,\text{fan}} \) - Estimated fan energy consumption in (kW) in each condition.

\( R_{1}, R_{\text{duct}} \) - Air flow resistance factor for each component and ducts, see Table 4-2

\( \dot{M}_{c,i}, \dot{M}_{c,\text{supply}} \) - Air mass flow rate in (kg/s) in each component and the total supplied air to the zones

\( \eta_{\text{fan}} \) - Fan efficiency

\( N \) - Total number of components in the configuration

4.2.3 Constraints for Optimisation

The constraints for HVAC configuration synthesis include 3 categories. The first category is concerning the formulation of the optimisation problem. As there are 3 types of design variables that are dependant to each other, the formulation of the variables has to be checked before anything else.

The second category is feasibility of the topology of configuration. As the topology represents the air flow network in the synthesised system, it has to be checked for:

- Connectivity – the components in the HVAC system have to be connected in order that air circulates in the system. The topology of HVAC system is defined as directed graph (digraph). The digraph has to be strongly connected, which means at least one loop exists between any two components in which air can circulate to and fro. Connectivity of the topology of generated HVAC configuration is one of the primary constraints. It will be not possible to perform further analysis on the configuration without satisfying the connectivity constraint first.
• Insensitive structure - a number of sub-structures in the topology are defined as "insensitive". These include self-loops, coupled DIV and MIX, and Digons. Figure 4-10 shows examples of insensitive structures.

![Diagram of insensitive structures]

Figure 4-10 Insignificant structures for HVAC system topology

The third category of constraints ensures correct operation of the configuration in each condition. These include the capacity and performance limits for each component (see Table 4-1 and Table 4-3); the design requirements for the occupied zones (from design brief); and other preferences.

Penalty function for constraints

The penalty functions for the optimization has 2 tiers. The first tier includes problem formulation and topology-related constraints. The second tier is the operation-related constraints. All constraints in the first tier have to be met before the constraints in the second tier can be checked. The evaluation of the objective function will also be impossible if any violation exists in the first tier of constraints. Table 4-4 lists the tier 1 constraints.

<table>
<thead>
<tr>
<th>ID</th>
<th>Description</th>
<th>Constraint value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1.1</td>
<td>Integrity of component set variables</td>
<td>1.0</td>
</tr>
<tr>
<td>C1.2</td>
<td>Integrity of topology variables</td>
<td>1.0</td>
</tr>
<tr>
<td>C1.3</td>
<td>Valences rule of topology</td>
<td>1.0</td>
</tr>
<tr>
<td>C1.4</td>
<td>Loop in topology</td>
<td>1.0</td>
</tr>
<tr>
<td>C1.5</td>
<td>DIV/MIX pair in topology</td>
<td>1.0</td>
</tr>
<tr>
<td>C1.6</td>
<td>Digon in topology</td>
<td>1.0</td>
</tr>
<tr>
<td>C1.7</td>
<td>Connectivity of topology</td>
<td>1.0</td>
</tr>
<tr>
<td>C1.8</td>
<td>Strong connectivity of topology</td>
<td>1.0</td>
</tr>
<tr>
<td>C1.9</td>
<td>Integrity of flow rates and duties variables</td>
<td>1.0</td>
</tr>
</tbody>
</table>

The constraints in tier 1 are qualitative constraints, whose penalty functions give either true or false on violations. As there are 9 constraints in this tier, the penalty function normalizes the output with the following equation:
Chapter 4 The configuration optimisation problem

\[ C_1 = \frac{\sum_{i=1}^{9} C_{1,i}}{9.0} \]  
(4-24)

The tier 2 constraints reflect the operational and design requirements. In the following equations, \( J, N, K \) stand for number of operation conditions, number of components, and number of zones respectively.

\[ C_{2.1} = \begin{cases} 1.0, & \text{When configuration model fails to create} \\ 0.0, & \text{otherwise} \end{cases} \]  
(4-25)

\[ C_{2.2,j} = \begin{cases} 0.0, & \text{airflows solvable} \\ \min(C_{2.3,j,n}, 3.0)^2, & \text{otherwise} \end{cases} \]  
(4-26)

Where, \( C_{2.3,j,n} = J \cdot N + 3J \cdot K \), is the maximum accumulative constraint value for group 2 constraints; \( Err_{\text{flow}} \) (kg/s) is the absolute value of the negative flow rate resulted from incorrect flow rate assignment.

\[ C_{2.3,j,n} = \frac{\sum C_{2.3,j,n}}{4} \]  
(4-27)

C2.1 Configuration model creation failure – after integration check for problem formulation and topology connectivity, there are still chances that the configuration model fails to construct. One of the main causes is the presence of cycles that do not involve either Ambient, or Zone component. As Ambient and Zone components represent known air conditions in the system, a cycle without Ambient or Zone cannot be solved by topological sorting. Therefore construction of configuration model will fail. Failure in model construction incurs a penalty as given in the following equation.

C2.2 Solvability of airflows – section 4.1.3 described how air flow rates in the system are solved after the flow rates are specified at certain branches. The flow rates may however be incorrectly specified and result in negative flows in other branches. If this happens, a constraint value in proportion to the negative flow rate is given.

\[ C_{2.3,j,n} = \]
C2.3.1 \( \dot{m}_{\text{in}} \)  Air flow rate – the capacity limit for a component handling air flow.

\[
C2.3.1_{\dot{m}} = \min\left(\frac{\min((\dot{m}_{\text{min}} - \dot{m}_{\text{in}}), \dot{m}_{\text{min}})}{\dot{m}_{\text{min}}}, \min((\dot{m}_{\text{in}} - \dot{m}_{\text{max}}), \dot{m}_{\text{max}})\right)^2
\]  \hspace{1cm} (4-28)

Where, \( \dot{m}_{\text{min}} \) and \( \dot{m}_{\text{max}} \) is listed in Table 4-3.

C2.3.2 \( T_{\text{hi}} \)  High temperature – the maximum air temperature a component can handle.

\[
C2.3.2_{T_{\text{hi}}} = \left[ \min\left(\max\left((T_{\text{hi}} - T_{\text{max}}), 0.0\right), 10.0\right) \right]^2
\]  \hspace{1cm} (4-29)

Where, \( T_{\text{max}} \) is listed Table 4-3.

C2.3.3 \( T_{\text{lo}} \)  Low temperature – the lowest air temperature a component can handle.

\[
C2.3.3_{T_{\text{lo}}} = \left[ \min\left(\max\left((T_{\text{min}} - T_{\text{lo}}), 0.0\right), 10.0\right) \right]^2
\]  \hspace{1cm} (4-30)

Where, \( T_{\text{min}} \) is listed in Table 4-3.

C2.3.4 \( \dot{m}_{\text{f}} \)  Condensation – condensation inside of a component may be not preferred.

\[
C2.3.4_{\dot{m}_{\text{f}}} = \begin{cases} 1.0, & \text{When undesirable condensation occurs} \\ 0.0, & \text{otherwise} \end{cases}
\]  \hspace{1cm} (4-31)

C2.4 \( \dot{m}_{\text{a}} \)  Fresh air supply – the fresh air supply to the occupied zones is crucial for health and air quality reasons. It can also be used on the Ambient component for detecting shortcut of fresh air.

\[
C2.4_{\dot{m}_{\text{a}}} = \left[ \min\left(\max\left((\dot{m}_{\text{a}} - \dot{m}_{\text{min}}), 0.0\right), \dot{m}_{\text{max}}\right) \right]^2
\]  \hspace{1cm} (4-32)

Where, \( \dot{m}_{\text{a}} \) and \( \dot{m}_{\text{min}} \) are listed Table 4-3.
C2.5_{j,k} \quad Zone \ supply \ air \ temperature - \ error \ between \ achieved \ and \ desired \ supply \ air \ temperature \ is \ used \ to \ calculate \ penalty \ for \ unsatisfied \ zone \ temperature \ requirement.

\[
C2.5_{j,k} = \begin{cases} 
0.0 & \text{, if } |T_{\text{sup}} - T_{\text{desire}}| < \varepsilon_T \\
\left[ \min\left(\frac{5.0}{\dot{m}_{\text{sup}}}, \frac{|T_{\text{sup}} - T_{\text{desire}}|}{\dot{m}_{\text{sup}}} \right) \right]^2 & \text{, otherwise} 
\end{cases}
\] (4-33)

Where,

\[T_{\text{sup}}\quad \text{Achieved supply air temperature.}\]

\[T_{\text{desire}} = T_z - \frac{Q_z}{\dot{m}_{\text{sup}}C_p} \quad \text{Desired supply temperature calculated from design zone temperature (} T_z \text{), sensible load (} Q_z \text{), and supplied air mass flow rate (} \dot{m}_{\text{sup}} \text{).}\]

\[\varepsilon_T = 0.2^\circ C \quad \text{Supply temperature tolerance}\]

C2.6_{j,k} \quad Zone \ supply \ air \ moisture \ content - \ error \ between \ achieved \ and \ desired \ supply \ air \ moisture \ content \ is \ used \ to \ calculate \ penalty \ for \ unsatisfied \ zone \ humidity \ requirement.

\[
C2.6_{j,k} = \begin{cases} 
0.0 & \text{, if } |\varepsilon_{\text{sup}} - \varepsilon_{\text{desire}}| < \varepsilon_g \\
\left[ \min\left(\frac{0.005}{\dot{m}_{\text{sup}}}, \frac{|\varepsilon_{\text{sup}} - \varepsilon_{\text{desire}}|}{\dot{m}_{\text{sup}}} \right) \right]^2 & \text{, otherwise} 
\end{cases}
\] (4-34)

Where,

\[\varepsilon_{\text{sup}} \quad \text{Achieved supply air moisture content.}\]
\[ \varepsilon_{\text{desired}} = \varepsilon_s - \frac{Q_i}{\dot{m}_{\text{sup}} C_p v} \]

Desired supply moisture content calculated from design zone moisture content \( (\varepsilon_s) \), latent load \( (Q_i) \), and supplied air mass flow rate \( (\dot{m}_{\text{sup}}) \).

\[ \varepsilon_s = 0.00075 \text{kg/kg} \]

Supply moisture content tolerance. For supply air at condition 20°C/50%, it is equivalent to 5% error in relative humidity.

Constraint values are accumulated and normalized for the tier 2 constraints using the following equation:

\[
C_2 = \max \left\{ \frac{\sum_{I \in N} C_{2.2_1} \left( \sum_{j \in J} \left[ \sum_{I \in N} C_{2.3_1} j + \sum_{I \in K} \left( C_{2.4_1} j + C_{2.5_1} j + C_{2.6_1} j \right) \right] \right)}{2 \cdot C_{2_{\text{norm}}}} \right\} (4-35)
\]

The overall infeasibility score is calculated from \( C1 \) and \( C2 \) using the following equation:

\[
\text{Infeasibility} = \begin{cases} 
0.9 + 0.1 \times C1, & C1 > 0.0 \\
0.9 \times C2, & C1 = 0.0 
\end{cases} (4-36)
\]

The primary purpose of normalization and scaling is to smooth the feasibility landscape of the solutions, and reduce multimodality. Figure 4-11 and Figure 4-12 show the surface of feasibility \((1 - \text{constraint value})\). The example is taken from the optimised operation of single-duct VAV configuration. Figure 4-11 shows the section against two operation variables, the heating coil output and the recirculation rate. The surface is largely smooth, despite the discontinuity on the lower side of airflow.

The impact of air flow rates is more clearly shown in Figure 4-12, where the section of feasibility surface is taken against two recirculation flow rate variables. In this example, flow rate 2 has to be higher than flow rate 1 to avoid violation of constraint C2.2. This situation is commonly seen in complex configurations. Further discussion will be given in Chapter 7.
Chapter 4 The configuration optimisation problem

4.2.3 Determination of configuration synthesis problem

The characteristics of the process can be represented as a 3-D surface, indicating that the problem is well constrained by the constraints of the heating coil duty and the recirculation air flow rate. This indicates that the optimization problem is highly constrained.

Figure 4-11 Example feasibility surface illustrated against heating coil duty and recirculation air flow rate

Note that a feasible solution should have feasibility value "1.0" (infeasibility = 0.0). It is a small flat spot on top of the surface plot, which cannot be seen in either of the figures. This indicates that the optimization problem is highly constrained.

Figure 4-12 Example feasibility surface illustrated against 2 re-circulation air flow rates
4.2.4 Characteristics of configuration synthesis problem

The characteristics of the present configuration synthesis problem can be summarized as 2-tier, highly constrained, and multi-modal problem. The first tier of the problem is the construction of HVAC configurations, which includes components and topology. It is a graph-based combinatorial problem. This class of problems are known to have large search space to the order of $O(N!)$ or $O(N^N)$, where $N$ is the degree of freedom. Many of them are hard to solve, or in other words, do not have a known algorithm to solve them in polynomial time. The second tier of the problem is highly constrained, non-linear, and discontinuous, as illustrated in Figure 4-11 and Figure 4-12.

Combining the two tiers, the landscape of the configuration synthesis problem can be analogously illustrated in Figure 4-13. Each peak (in terms of fitness) stands for a viable configuration, whereas the tip of the peak represents optimal operation of the configuration. The quality of the configurations is defined only by the absolute height of the peak. Meanwhile, the heights of the peaks may be very similar (Chapter 7 and Chapter 8 will provide further discussion). Given the nature of the problem, a robust optimization algorithm is required to tackle it.

![Figure 4-13 Illustration of multimodality of the configuration synthesis problem](image-url)
4.3 Summary

In this chapter, the content of the configuration model has been defined. An HVAC configuration is comprised of a set of components, an airflow network that connects the components, and sets of air flow rates and capacities that define the operation of system under each condition. Psychrometric models and airflow models have been developed for the components.

The characteristics of the airflow network of HVAC configurations are discussed. First of all, in order to allow air being circulated between the ambient environment and the air-conditioned spaces, the network has to be “closed”, or strongly connected in term of graph theory. There are other constraints that help to define an available configuration topology. Graph-based analysis also helps in understanding the topology, and solving the operation of the configuration.

The operation of an HVAC system defined by a configuration is determined by a set of parameters, which include a number of air flow rates, and capacities associated with the components. The method used in extracting the parameters, and henceforth solving the operation of the system with these parameter values, is introduced. The configuration model provides the basis for optimisation.

The second part of this chapter concentrated on the formulation of the optimisation problem for configuration synthesis. For an optimisation problem, normally expressed as “to minimise (maximise) (an) objective(s), which is subject to a number of constraints”, two fundamental elements have to be defined. For the configuration synthesis problem in this research, the objective is to minimise the energy consumption of the system on the annual basis. In other words, though subjected to various operation conditions, the synthesised system should consume the least energy by the end of year.

The constraints for the configuration problem ensure that the synthesised configuration is (1) physically possible; (2) able to fulfil the design requirement with the available resources. The constraints for the problem are arranged in two levels, depending on the severity of the constraint if violated. The detailed definition was discussed.
In the previous chapter, the HVAC system configuration synthesis problem is formulated as an optimisation problem. This chapter describes the implementation of the optimisation algorithm for the particular problem. The configuration synthesis problem is a combinatorial, constrained, and multi-modal. Evolutionary algorithms (EAs) are known to be versatile and robust. The general process of EAs and the typical variations have been reviewed in Chapter 2. In short, the main part of an EA is the evaluation-reproduction loop. EAs work on a "population" of solutions. The evaluation process assesses the fitness of each solution in the population, whereas the reproduction process produce new solutions from the existing solutions based on their fitness. The whole evolutionary process is driven by the "survival of the fitness" concept from Darwin’s natural selection theory.

As a class of optimisation methods, a number of ingredients of an Evolutionary Algorithms are important to its behaviour and performance. Firstly, the EA work on the numerical representation of an optimisation problem, the Genome. The data structure of the genome determines how the evolutionary processes can be implemented; subsequently, affects the behaviour of the evolutionary algorithm. The realization of the evaluation-reproduction loop is also important, as the choice of operations for fitness shaping, selection, reproduction, and elitism contributes to the algorithm performance.
In this chapter, the design of the configuration genome is first introduced in 5.1. The unique structure of the configuration genome requires specially formulated reproduction operators, which are introduced in 5.2. The implementation details of the EA are given in 5.3. The problem-specific operators, as one of the major developments in this research, will be discussed separately in Chapter 6.

5.1 Design of the genome

Optimization with evolutionary algorithms requires the problem being defined in two different domains – the genotypic domain and the phenotypic domain. The genotypic domain contains the numerical encoding of the optimization problem variables. The phenotypic domain contains models of the assessable targets, such as physical phenomena or objects. The encoding/decoding function maps the optimization problem between genotypic and phenotypic spaces. The design of the data structures in both domains is important, because:

- Evolutionary algorithms only operate in genotypic domain; therefore implementation of problem-specific algorithms relies on the design of genotypic data structure.

- Good phenotypic data structure design is the basis for modelling and evaluation of the candidate solutions.

- The computational overhead for encoding and decoding between the genotypic and phenotypic domains can be minimized by adopting appropriate data structures.

The classic genetic algorithm (GA), one of the many forms of Evolutionary Algorithms, uses binary-encoded chromosome that contain a single binary string. Though generality is emphasized, it is relatively difficult to implement problem-specific operators with GA. Many problem-customized evolutionary algorithms use real-encoded chromosomes, or other data structures. The obvious benefits of this choice are better representation of the structure of the given problem, and reduced encoding/decoding complexity. In this research, the approach for HVAC configuration synthesis involves simultaneous structural and parametric optimization. The design of the genotype that encodes both structural and parametric problem variables into a unified evolvable data structure is crucial. The Genome for HVAC configuration has been developed. It contains a set of member chromosomes, each of which represents a sub-problem in configuration synthesis.
5.1.1 Encoding of HVAC configuration

The configuration of HVAC system comprises three parts, the components, the topology, and the operations. Three sets of chromosomes have been defined to encode the different parts, respectively. These are ComponentSet chromosome, Topology chromosome, and Operation chromosome.

ComponentSet chromosome

The ComponentSet chromosome is an integer string that encodes the list of components in the configuration. Each gene in the ComponentSet chromosome identifies the type of the component. The available component types are listed in Chapter 3, Table 3.1. The following figure shows an example of the ComponentSet chromosome (Figure 5-1).

![Figure 5-1 Example of ComponentSet chromosome](image)

The encoding provides two parts of information about a component in the configuration. The gene number serves as a unique ID for the component in the set, whereas the gene value indicates the type of the component. Therefore each and every component is uniquely identified, e.g. the fourth gene in the example, whose value is “1”, identifies MIX(3) in the component set.

The list of components is always sorted by their Type IDs (see Chapter 3, Table 3-1) before encoded into chromosome. Therefore the diverging tees (DIVs) are always at the beginning of each chromosome, while the Ambient is always the last gene. Keeping the component list sorted has two benefits. First, it ensures that the encoding of the component set is unique (i.e. same set of components always produces same encoding); and second, it helps to keep the topology encoding compact and efficient. This will be further explained with the design of Topology chromosome.
**Topology chromosome**

The Topology chromosome is also a string of integers. It is a modified adjacency representation of the underlying digraph of the network. Table 5-1 shows three typical encodings of digraph. The full adjacency matrix is an N-by-N binary array, in which "1" in row $i$, column $j$ indicates the $i^{th}$ component is connected to the $j^{th}$. Binary encoding is inherently suitable for Genetic Algorithm to process; it is the least efficient encoding, however, as the "0"s in the array are redundant.

<table>
<thead>
<tr>
<th>Representation</th>
<th>Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full adjacency matrix</td>
<td><strong>Graph</strong></td>
</tr>
<tr>
<td></td>
<td>From</td>
</tr>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Edge-list</td>
<td>Edges</td>
</tr>
<tr>
<td></td>
<td>&quot;From's&quot;</td>
</tr>
<tr>
<td></td>
<td>0 1 2 3 4 4</td>
</tr>
<tr>
<td></td>
<td>1 2 3 4 1 0</td>
</tr>
<tr>
<td></td>
<td>&quot;To's&quot;</td>
</tr>
<tr>
<td>Adjacency</td>
<td>Componentset</td>
</tr>
<tr>
<td></td>
<td>2 1 2 3 4</td>
</tr>
<tr>
<td></td>
<td>&quot;From's&quot;</td>
</tr>
<tr>
<td></td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td></td>
<td>Indices</td>
</tr>
<tr>
<td></td>
<td>0 1 2 3 4 5</td>
</tr>
<tr>
<td></td>
<td>&quot;To's&quot;</td>
</tr>
</tbody>
</table>
The Adjacency encoding uses two rows of numbers as well. The first row, however, is a list of pointers to the second row. The first row has the same length as the component set; therefore each element indicates the location where the outgoing links of the correspondent component can be found in the second row. For example, the component “Z”, which is the fifth component in the list, has the point value “4” (the index starting at 0). The element in the second row at index “4” has a value of “1”. Therefore the component “Z” is connected to component “1”. As there are not any more pointers directing to the element at the index “5” in the second row, its link belongs to “Z” as well. Therefore “Z” is also connected to “A” (which has an index of “0”). The compacted adjacency encoding is slightly better than edge-list encoding. It requires only 11 integers to represent the digraph.

A more compact encoding has been designed for the configuration topology. Given that all components have only one outgoing link, except diverging tees, which has two, the indices array in the compacted adjacency encoding can be omitted. Consider a set of N components, the first N elements in the topology encoding identifies the first “out-going” link of each component. The next N elements in the topology encoding identify the second “out-going” links. As the diverging tees are always located at the beginning of the component set, only the first M elements in the second part are defined. Therefore the redundant elements can be omitted. See the following example.

![ComponentSet](image)

![Topology Encoding](image)

**Figure 5-2 Illustration of topology encoding**

The topology encoding for the example uses only 6 integers, which is much shorter than 11 for Compacted adjacency and 12 for Edge-list encodings. As a result, the topology chromosome is defined. Each gene of the Topology chromosome identifies an “out-going” link from the component at the correspondent position in the component list, to the component at a position indicated by the gene value. For the diverging tees (DIVs) that have two outgoing links, the secondary links are appended to the list of primary links of all components.

Clearly, the topology encoding developed in this research has the benefit of efficiency. As each gene in the chromosome is a problem variable, the length of the chromosome de-
fines the dimension of the search space. Consequently, shorter encoding is often preferred in optimisations.

**Operation chromosome**

Two groups of problem variables are involved in defining the operation of an HVAC system configuration (see Chapter 4, 4.2.1). The first group includes the air flow rates that describe the air circulation in the system; the second group contains the thermal duties of air-handling components. In this research, heating, cooling, and humidifying duties are associated with Heating coils, Cooling coils, and Steam injectors, respectively. The definition of the air flow rate variables is less straightforward. As discussed in section 4.1.3, the air circulation within the system can be determined by assigning airflows in a few branches. Theoretically, the branches to be assigned are determined by using a tree-growing method. Given the present topology problem, however, the branches whose airflow are to be assigned, are attached to either the Ambient component, or the MIX components. As a result, the composition of the Operation chromosome can be defined without graph analysis. For the example, the component set in Figure 5-1 contains 6 operation problem variables. They are 1 air flow rate to the Ambient(9), 2 air flow rates to the MIXs (2 and 3), 1 heating duty to Heat(4), 1 cooling duty to Cool(5), and 1 humidifying duty to Steam(6).

The Operation chromosome is consequently defined as a string of double-precision real variables. The order of the variables is arranged in the following sequence. The first gene represents the air flow rate to the Ambient component. The following $M$ genes are the input air flow rates to the $M$ MIX components. The next genes are the duty variables for the air-handling components. Figure 5-3 shows an example Operation chromosome for the component set in Figure 5-1.

<table>
<thead>
<tr>
<th>Gene:</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable:</td>
<td>$M_{\text{Ambient}}$</td>
<td>$M_{\text{MIX}_2}$</td>
<td>$M_{\text{MIX}_3}$</td>
<td>$Q_{\text{Heat}_4}$</td>
<td>$Q_{\text{Cool}_5}$</td>
<td>$M_{\text{Steam}_6}$</td>
</tr>
</tbody>
</table>

![Figure 5-3 Example FlowDuty chromosome](image)

### 5.1.2 Definition of genome

One ComponentSet chromosome, one Topology chromosome, and a number of Operation chromosomes are integrated into the Genome for HVAC system configuration. The operation chromosome encodes the control set points for one operation condition. Table 5-2 summarizes the definition of member chromosomes in the configuration genome. In Table
5-2, "N" is the number of components in the configuration; "M" is the number of DIVs (or MIX's); "J" is the number of operation conditions, hence, the number of Operation chromosomes; and "K" is the number of air-handling components (Heat, Cool, and Steam) in the configuration.

<table>
<thead>
<tr>
<th>Member chromosome</th>
<th>Gene type</th>
<th>Length</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ComponentSet</td>
<td>Integer</td>
<td>N</td>
<td>N components, in which there are M DIVs. The value of each gene is the type ID (see Chapter 3, Table 3-1) of the component in that position.</td>
</tr>
<tr>
<td>Topology</td>
<td>Integer</td>
<td>N + M</td>
<td>The topology chromosome is a list of &quot;to&quot; links. Each gene value is the index of component to which the present component is connected. For example, a &quot;4&quot; in gene 2 means the second component is connected to the fourth component. The list has two parts, the first N genes are the first outgoing links from each component. The second part contains the extra legs of the DIVs.</td>
</tr>
<tr>
<td>Operation 1</td>
<td>Double</td>
<td>1 + M + K</td>
<td>The Operation chromosome has also two parts. The first part is 1+M air mass flow rates (kg/s) associated to the Ambient and MIX's components. The second part is K capacities (kW) of air-handling components.</td>
</tr>
<tr>
<td>Operation 2</td>
<td>Double</td>
<td>1 + M + K</td>
<td></td>
</tr>
<tr>
<td>Operation ...</td>
<td>Double</td>
<td>1 + M + K</td>
<td></td>
</tr>
<tr>
<td>Operation J</td>
<td>Double</td>
<td>1 + M + K</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5-4 and Figure 5-5 give an example of genome encoding for the 2-zoned single-duct configuration. There are 14 components, in which, 3 are DIVs. In total, there are 17 links that connect the components together. In order to determine the operation of the configuration, 4 air flow rates and 5 duties are required.
The formation of the Topology chromosome and the Operation chromosomes are determined by the components in the ComponentSet chromosome. Figure 5-6 shows the dependencies between the member chromosomes. Apparently, the ComponentSet chromosome is the pivot member. Both Topology chromosome and Operation chromosomes are determined by its composition. During evolution, if the ComponentSet chromosome is changed, the present Topology and Operation chromosomes may become illegal, therefore have to be "repaired" accordingly. It is possible to provide a mechanism that allows the subsidiary chromosomes to correct themselves in response to the change in the ComponentSet chromosome. For example, in case a Heating coil is added to the ComponentSet, the algorithm
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should randomly choose a position in the topology to insert the new component; and add a
heating duty gene in each Operation chromosomes.

![HVAC configuration genome diagram]

**Figure 5-6 Organisation of the member chromosome in HVAC configuration genome**

Although it is possible to maintain the correct formation of the genome, the consequences
of changing the ComponentSet chromosome are likely to be highly destructive, in terms of
configuration fitness. Consider that a configuration genome has been optimised to some
extent, introducing a new component, or replacing an existing component at random intends
to degrade the performance of the configuration. On the other hand, removing a component
from the genome may be beneficial if the component to be removed is redundant (has zero
duty in all conditions).

Instead of repairing the genome whenever the ComponentSet chromosome is changed,
one alternative approach is to "freeze" the ComponentSet chromosome during the optimisation.
Firstly, a maximum set of components is selected. Optimisation of topology and operations is then performed with these components. As the ComponentSet chromosome is fixed,
the formation of the Topology and Operation chromosomes is stable during the optimisation;
therefore the demand for synchronization is removed. After optimisation, the redundant
components can be easily removed with a post-process. Because the maximum set of com-
ponents is used, the search space of this approach is equivalent to that of the variable Com-
ponentSet approach. As a result, both approaches should produce the same optimal
configurations.
5.1.3 Advances and limitations

The idea of the genome is to divide complex genotypic information into more manageable pieces (the member chromosomes). The member chromosomes can then be handled respectively. With specially designed reproduction operators, evolution can happen on both the aggregation level and the member level. For example, the Selective Duties crossover is a "mix-and-match" crossover working on the aggregation level. Consider that if two genomes share the same ComponentSet and Topology, the "mix-and-match" crossover picks the better Operation chromosomes from either genomes and forms a child genome that is better than both parents. On the other hand, the CoG crossover works on the member level, and calculates new Operation gene values from the genes in the parent chromosomes. In order to exploit the advances in this aggregative chromosome design, problem-specific operators have been developed. These operators will be discussed in detail in Chapter 6. The various operators that work on the genome and its member chromosomes are organized into the "hyper" operators. The definition of Hyper operators for configuration genome is given in section 5.2.

The framework of genome design is flexible and versatile. As an aggregation of member chromosomes, it also allows genomes to be nested, therefore capable of encoding complex problems. The interaction between the member chromosomes, however, is not represented in the data structure; therefore has to be implemented separately. This means a complex mechanism for synchronizing each member has to be developed to maintain the integrity of the Genome. This can be regarded as a disadvantage in certain applications.

5.1.4 Family and neighbourhood

In this research, "Family" and "Neighbourhood" are used to identify groups of solution genomes in each "population". One of the characteristics of the evolutionary algorithms is that they work on a number of solutions simultaneously. The set of solution genome that an EA optimises at a time is called one "Population". Families and neighbourhoods are subsets in a population. With the HVAC configuration design, a Family of genomes is defined as the group of genomes that share the same ComponentSet and Topology chromosomes. The genomes in the same family only differ in their Operation chromosomes.

There are two reasons for the introduction of Family. Firstly, in the present definition of the Operation chromosome, each gene is a flow rate or duty variable associated to a particu-
lar component. If the ComponentSet chromosomes of two genomes are different, the definitions of their Operation chromosomes are different, too. In case those ComponentSet chromosomes are the same, whereas the Topology chromosomes are different, the same component may be in different locations in the two configurations, therefore functions differently. As a result, the most efficient way to optimize the operation of a configuration is to ensure that evolution can happen within the family. This requires sufficient size of the family to be maintained in the population.

The second reason is, since Families are distinguished by components and topologies, statistics of families in the population provide information of configuration exploration. The evolutionary algorithm can be encouraged to explore more configurations, by enforcing the minimum number of families to be present in each population. A dynamic sharing method, the Ageing operator, has been developed to maintain diversity of families in the population, as well as the economical size of promising families. The Ageing operator will be further discussed in Chapter 6.

![Figure 5-7 Examples of neighbouring topologies](image)

In multi-modal optimisation problems, Neighbourhood refers to the region near a local optimum. For the HVAC configuration problem, the operation of different configurations
can be similar to each other. Such similarity is often caused by redundancy and isomorphism. Figure 5-7 shows two examples of neighbouring topologies. The topologies A and A’ are isomorphic. The only difference between them is the labels on the DIV components. Because the DIVs do not have any associated flow or duty variables, they are equivalent and indistinguishable. Therefore, although the chromosomes for A and A’ are different, the topologies are effectively identical.

Isomorphic topologies can also be found in configurations with redundant air-handling components. In Figure 5-7, the Heat(2) in both topology B and B’ does not take any duty in air-conditioning; therefore its location does not have any impact on the performance of the configuration. The topology B and B’ are considered equivalent.

Unlike Family, whose boundary is defined by ComponentSet and Topology chromosomes, the scope of Neighbourhood can be estimated by the Operation chromosomes. Practically, if two configurations whose optimal operational parameters are similar, they are likely to be within the same neighbourhood. Unfortunately, the boundary of a Neighbourhood is very difficult to identify. One possible analytical way is isomorphism analysis of the networks after the removal of redundant components. As the graph isomorphism problem is NP-Hard\(^6\) itself, it is out of the scope of this research. However, the concept of Neighbourhood is important for understanding the behaviour of the configuration synthesis algorithm, and deserves further study in the future.

### 5.2 Hyper reproduction operators

As to the genome design, each member chromosome needs its own set of operators. A mechanism is required to organize various operators and make them work together. In this section, the design of “Hyper” operator for genome is described.

#### 5.2.1 “Hyper” operator

A hyper operator is an assembly of member operators that are working together in an organized way. The member operators are those performing on different levels and on different member chromosomes. By coordinating the member operators, complex operation on the genomes can be defined.

\(^6\) NP-Hard: the complexity class of decision problems that is intrinsically harder than those that can be solved by a nondeterministic Turing machine in polynomial time. (see http://www.nist.gov/dads/HTML/nphard.html)
The member operators of a hyper operator work together in one of the three predefined manners:

- **Competitive**: The member operators compete to perform according to their assigned relative probability. This is useful when each of the operators has its merits and deficiency, yet they are conflicting with each other and cannot be executed at the same time. When the hyper operator is called, it tosses a coin to decide which of its member operators will be executed.

- **Sequential**: All of the members must perform, and perform in a sequence according to their positions in the list. This arrangement is necessary for organizing the operators for different levels/chromosomes, and the operators that can be executed at the same time.

- **Privileged**: The member operators try to execute one after another, in the order of their positions in the list. If one member has successfully performed, all of its followers are muted. As the performance of an operator is often conditional, the most preferable/beneficial operator is tried first, then the less preferable one, and so on.

By nesting hyper operators, complex behaviour can be defined. The following figures are the definition of hyper crossover and hyper mutation for genome in the implementation. The notations used in the diagrams are explained in Figure 5-8. The first element is the type of the operator. The number following the type is the probability of execution when this operator is called. The third element is the weight of the operator in its group. The weight is only used in competitive mode, where the chance of this operator being called is determined by its weight divided by the total weight. The last element indicates the cooperation mode of the group.
5.2.2 Recombination – crossover

The recombination operators, or crossovers, are used to produce new solutions from existing candidates, by mixing and combining their features. For the configuration synthesis problem, each solution has the features in both the structure of the configuration, and its operation. The proper crossovers need to be able to handle both types of features effectively.

Figure 5-9 shows the composition of the hyper crossover for configuration genomes. From outside (the top level), it is a single crossover operator that works on selected genomes. Inside of it, it has two major members, the SelectiveDuties crossover and the member-level crossover group. The definition of the SelectiveDuties crossover will be detailed in Chapter 6. Briefly, it picks better Operation chromosomes from the existing solutions to make an overall better solution. This operator is the best-preferred operator. Therefore if it is performed, other operators can be ignored. The member-level crossover group consists of the crossovers for the Topology chromosome and crossovers for the Operation chromosomes respectively. Note that the probability of execution for the topology operator group (0.5) is lower than that for the Operation operators (1.0). This helps maintain the stability of the topologies. The details of the Topology-specific operators and the Operation-specific operators are to be discussed in the following sections.

Figure 5-9 Definition of hyper crossover
A high probability of crossover is commonly used in topological optimization problems (typically 100%) [Koz03]. However, a 100% topology crossover was found to be too disruptive, often resulting in infeasible solutions; a lower rate of 50% probability was found to give good algorithm performance.

5.2.3 Mutation

The mutation operators are normally applied on the new solutions that have been generated by the crossovers. They disturb the new solutions in order to encourage exploration. Figure 5-10 illustrates the definition of the hyper mutation operator for configuration genomes. There are only two groups of mutation operators for the Topology chromosome and the Operation chromosomes respectively. Again the disturbance to the Topology chromosomes is much lower than to Operation chromosomes. The elementary members of the mutation operator are further discussed in Chapter 6.

![Figure 5-10 Definition of hyper mutator](image)

Similarly to the crossover operator, a high mutation rate on the topology chromosomes was found to result in poor convergence on a feasible solution, and therefore was assigned a lower modifier (0.2) than for the air flow rate and component capacity chromosomes (1.0). Given the probability of mutation at 10%, the probability of the topology chromosome to be changed is 0.2*10%=2%; whereas the probability for an Operation chromosome is 10%.
5.3 Implementation of Evolutionary Algorithm

Figure 5-11 presents the implementation of Evolutionary Algorithm for HVAC configuration synthesis. Optimisation starts with a randomly generated population of solution genomes. The existing configurations, and the solutions found from previous optimisations, can be used as seeds in the initial population. Once the initial population is prepared, the process of EA goes into the evaluation-reproduction loop, until the termination condition has been satisfied.

![Figure 5-11 Realization of Evolutionary Algorithm](image)

In the evaluation-reproduction loop, the solution genomes in the current population are evaluated for their fitness according to the problem's objective and constraint functions (0). Fitness shaping methods, such as scaling, ranking and sharing, are often used to determine the relative quality of the solutions; therefore assisting in guiding the direction of search, as
well as controlling the selection pressure. Stochastic Ranking (5.3.2) and Ageing (Chapter 6, 6.3) are used in this approach. The evaluated solutions are then passed to two reproduction channels. The normal reproduction channel consists Selection, Crossover, and Mutation operations. The 1-in-2-tournament method is used for selecting parent genomes (5.3.4). Problem-specific Hyper Crossover and Hyper Mutation operators are used to produce new solutions for the next generation (5.3.5). The Elitism channel copies the best solutions in the present population directly to the new population (5.3.6). EA exits the evaluation-reproduction once the maximum number of generations has been reached.

5.3.1 Evaluation of genomes

To evaluate a solution, the configuration model is created from the genome. The performance of the configuration can then be evaluated. As energy consumption is the primary concern in this research, the coil duties and circulation cost (fan power) in each design condition are summated to estimate annual energy consumption of the system. Satisfaction of the design constraints is also checked (see Chapter 4, section 4.2 for the definition of the objective and constraint functions).

The following steps are performed to evaluate each genome:

Step 1 – Check the integrity of the genome

- Check the composition of the genome, i.e. the formation of ComponentSet, Topology, and Operation chromosomes, and their relations.
- Check the Topology chromosome with the connectivity rules, including insignificant structures and strong connectivity.

Step 2 – Express the genome and create configuration model

- Create configuration model from ComponentSet and Topology chromosomes.
- Assign control set points from Operation chromosome for each operation condition; solve airflows, fresh air proportion, and psychrometric conditions with the methods provided in Chapter 4, section 4.1.

Step 3 – Evaluate the configuration under each operation condition

- Check component operation constraints.
- Check supply air condition and fresh air supply for each zone.
- Calculate energy consumption by accumulating coil duties and circulation cost.
- Calculate the estimated annual energy consumption from weighted sum of all conditions.

Step 4 – Calculate constraint function and objective function values

- Summate and normalize the penalties received from different constraints; calculate constraint function and objective function; and return the infeasibility score and the objective value of the candidate.

5.3.2 Stochastic ranking

The results of genome evaluation are two real values of infeasibility and objective, respectively. A fitness ranking method is used to combine the infeasibility and objective to provide the assessment of the quality of the solution. Different constraint-handling approaches are available for fitness ranking: to name a few, there are penalty function [Deb01], multi-objective [Loo03], self-adaptive [Far03], and stochastic ranking [Run00]. The stochastic ranking was originally introduced by Runarsson and Yao [Run00]. It uses a bubblesort-like algorithm, while the comparison of solutions is on either their infeasibility values or objectives stochastically. List 5-1 shows the implemented stochastic ranking algorithm.

```plaintext
// In the present population of N solutions
For I = 2 to N,  // for each solution from the second to the last
    For J = I down to 2 // compare this solution to the ones above it
        Compare = toss_a_coin (INFEASIBILITY, OBJECTIVE);
        If (solution [j].infeas == solution [j-1].infeas OR Compare == OBJECTIVE)
            If (solution[j].objective < solution [j-1].objective)
                Swap (solution [j], solution [j-1]);
                End if
        Else
            If (solution [j].objective < solution [j-1].objective)
                Swap (solution [j], solution [j-1]);
                End if
        End if
Next J
Next I
// Assign the final position of each solution in the population as its fitness rank and return.
```

List 5-1 Algorithm for Stochastic Ranking

The Stochastic ranking method has the advantage of balancing the efforts to minimize infeasibility and objective at the same time. It uses one parameter to control the bias between
ranking on infeasibility or objective. If the parameter is 0.5, the algorithm ranks on infeasibility and objective with equal probability. A factor less than 0.5 biases the algorithm towards infeasibility. According to the authors, 0.45 is a generally good choice for the control parameter \cite{Run00}.

5.3.3 Sharing

The configuration synthesis problem is a multi-modal problem. The landscape of the search space often has many peaks (or valleys for minimisation problems) of similar heights. In order to avoid premature convergence on a local optimum, sharing algorithms can be used. Sharing is an operation that modifies the fitness of individuals in the population, so as to encourage the formation of sub-populations that converge toward different solutions. To achieve this, for each individual in the population, the algorithm identifies how many individuals are similar to it. The more individuals are similar to it, the further degradation in fitness is applied to the individual. As the result, the relative fitness of dissimilar solutions is boosted; therefore diversity in the population is encouraged.

Similarity between individual solutions of HVAC configuration is defined by the ComponentSet and Topology chromosomes they have (see “family” in Section 5.1.4). A sharing algorithm should help to encourage exploration of configurations. In this research, the “Ageing” operator is developed. It will be discussed in detail in Chapter 6.

5.3.4 Selection

Selection operation selects candidates for reproduction from the current population. The solutions are normally selected on their fitness; therefore the fittest individual has the best chance of reproduce itself. An appropriate selection method provides sufficient “selection pressure” to move the search towards the optimum. Generally, the more selection pressure applied to a search, the faster the solutions converge, however, with higher risk, to a local optimum. On the other hand, if the selection pressure is weak, the convergence of the search may be too slow, and cannot find a good solution in reasonable time. It is important to apply appropriate selection pressure to the search, with consideration of the characteristics of the problem.

The most commonly used methods are Roulette Wheel and Tournament selections \cite{GoI89}. As ranking method is used in the present approach, the fitness of solutions is their
ranks in the population, such that the best solution has a fitness value "1", the second best has a value "2", and so forth. In this case, the Roulette Wheel selection and the 1-in-2-Tournament selection are equivalent. The "1-from-2" Tournament selection is implemented in this research.

5.3.5 Reproduction

The reproduction is the combined process of Selection – Crossover – Mutation. Candidate solutions are selected by the selection method, and then put to the recombination operator in pairs. The recombination operator produces new solutions from the existing candidates. The new solutions are then passed to the mutation operator. The mutated solutions are inserted into the next generation. The design of reproduction operators (crossover and mutation) is crucial to the performance of the evolutionary algorithm. The problem-specific operators have been developed for configuration synthesis. These operators will be discussed in the next chapter.

5.3.6 Elitism

In parallel to the reproduction path, an elitist method copies selected solutions in the present population to the next generation. Elitism is a means to maintain the quality of population through generations. As evolutionary algorithm is a stochastic process, chances are good solutions discovered in present population may be lost. The elitism algorithm copies the best solutions in the present population into the next population.

The present implementation of the elitism is using the population overlap. Since the solutions are rank ordered in terms of their fitness, a population of a 1,000 and a 2% overlap of solutions, will results in the top 20 ranked individuals being copied directly to the next generation.

5.4 Summary

In this chapter, the implementation of the Evolutionary Algorithm (EA) for HVAC configuration synthesis problem has been described. The multi-level nature of the configuration problem requires the new design of genotype. The genome for HVAC configuration synthesis was developed. A genome is comprised of a number of member chromosomes, which encodes the components, the topology, and the control set points in each operation condition.
Chapter 5 The Evolutionary Algorithm

The member chromosomes are not isolated, but organized in a structure, in which the formation of Topology and Operation chromosomes depends on the ComponentSet chromosome. Special reproduction operators have also been developed for the genome design. The Hyper crossover and Hyper mutation operator have member operators working together on the genome and each member chromosomes.

Although the genome design has the advantage of flexibility, it requires explicit synchronisation method to coordinate changes in member chromosomes during the evolution. This problem is simplified in this research, by “freezing” the ComponentSet chromosome during the search. The evaluation – reproduction loop of EA is then described. The implementation of EA in this research is consisted of a number of operations, which work together to perform the evolution loop. Table 5-3 summarized the choice of operations and their parameters. Unless otherwise stated, the algorithm control parameters used in this study are those given in Table 5-3.

Table 5-3 Optimization Algorithm Control Parameters

<table>
<thead>
<tr>
<th>Operation</th>
<th>Control Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population</td>
<td>Population Size</td>
<td>1,000</td>
</tr>
<tr>
<td></td>
<td>Maximum Generations</td>
<td>10,000</td>
</tr>
<tr>
<td></td>
<td>Population Overlap</td>
<td>2%</td>
</tr>
<tr>
<td>Selection (Tournament Selection)</td>
<td>Tournament Type</td>
<td>1 from 2</td>
</tr>
<tr>
<td>Crossover (Hyper genome crossover*)</td>
<td>Topology Probability</td>
<td>50%</td>
</tr>
<tr>
<td></td>
<td>Operation Probability</td>
<td>100%</td>
</tr>
<tr>
<td>Mutation (Hyper genome mutation*)</td>
<td>Topology Probability</td>
<td>2%</td>
</tr>
<tr>
<td></td>
<td>Operation Probability</td>
<td>10%</td>
</tr>
<tr>
<td>Fitness ranking (Stochastic Ranking)</td>
<td>Probability of Infeasible Solution Ranking</td>
<td>45%</td>
</tr>
<tr>
<td>Sharing (Ageing*)</td>
<td>Maximum Evaluations per Generation</td>
<td>20</td>
</tr>
<tr>
<td>Elitism</td>
<td>Population overlap</td>
<td>2%</td>
</tr>
</tbody>
</table>

* The problem-specific development for HVAC configuration synthesis, including topology-specific and operation-specific reproduction operators and Ageing, is discussed in next chapter.
Chapter 6

Problem-specific algorithm operators

The classic genetic algorithms are claimed to be neutral to any specific optimization problem, thanks to its binary encoding and standardized operators. Many other evolutionary algorithms employ problem-specific encodings and operators. It is often true that the more domain knowledge of the problem being incorporated in the algorithm design, the better it performs. The use of problem-specific operators normally enhances performance of the evolutionary algorithms. The optimization problem for HVAC system configuration synthesis is a combinatorial, mixed integer, and non-linear problem. Its multi-modality and highly constrained nature makes it very hard to solve. Problem specific operators have been developed in this research, in order to tackle the problem from three directions: (1) non-destructive exploration, (2) faster exploitation of local optima, and (3) maintenance of diversity by enhancing search beyond neighbourhood.

In this chapter, the problem-specific reproduction operators for the Topology chromosomes and the Operation chromosomes are analyzed. The “Ageing” operator is also introduced as a dynamic speciation method, to enhance exploration of the topological space.
6.1 Reproduction operators for the Topology chromosome

The configuration synthesis has two connected optimization problems; search for feasible configurations and optimization of operations of the feasible configurations. The candidate configuration has to be feasible first, in terms of being capable of circulating air between ambient and zones, before its operation can be solved. Naturally, the effectiveness in searching for feasible configurations, and once found, maintaining their feasibility, is the primary issue for the search algorithm.

The major difficulties for topology optimisation are related to large search space and discontinuity. The topology problem is a combinatorial problem. The size of the search space can be estimated by the encoding. For an integer string encoding, the total variation is $X^Y$, where $X$ is the range of values of each gene, and $Y$ is the length of the string. Consider the encoding of topology (Chapter 5, 5.1.1), the chromosome is a string of $N+M$ integers. Each integer number (gene) represents the index of the component to which the current component is linked. Given the number of components is $N$, each topology gene can take a value between 0 and $(N - 1)$ as the index is 0-based. The length of the topology string is $(N + M)$, where $M$ is the number of DIVs who has a second outgoing link. As a result, the maximum search space for topology encoding is $N^{(N+M)}$. For a configuration such as a single duct system, it has 14 components ($N=14$), among which there are 3 DIVs ($M=3$). The length of the topology chromosome is $N+M=17$, therefore $14^{17} \sim 3.05\times10^{19}$ variations exist. The standard integer string operators, such as 1-point crossover and Flip mutation, are working in this space.

The size of encoding variations can be reduced by reinforcing certain formation rules at creation stage. A valid encoding for the underlying graph of the topology has to abide by the valences rule. The valences rule is that each and every output port of the components is linked to one and only one input port, and vice versa. The first part of the rule is naturally satisfied by the definition of the chromosome, where each gene represents an output port of the correspondent component. The second part of the rule is only satisfied if the indexes of the MIXs appear twice, whereas the indexes of other components appear once, in the topology string. It is possible to develop algorithms to initialise and reproduce topology chromosomes that comply with the valences rule. These algorithms, or operators, will be defined in this section.
With valences-rule-complying encoding, the search space of topology strings is the sequences of a set of pre-determined integer values, the indexes of the components in the topology. The set of values includes integer 0 to \((N - 1)\), plus the duplicate indexes of MIXs. There are total of \(\frac{(N + M)!}{2^M}\) possible variations of sequence. That is, for the configurations as "complex" as a single duct system, where \(N=14\) and \(M=3\), the variations count is \(17!/8 = 4.45 \times 10^{13}\). It is about a millionth of the space of the original integer string. In the refined search space, however, only about 1% of the topology strings are feasible according to other topological constraints. This condition can be illustrated by considering a population of 1000 solutions. In the population, there may be only 10 solutions whose topologies are feasible. Since it is not possible to evaluate operational variables without a feasible topology, the operation of the solutions cannot be evolved efficiently. Topology-specific operators are needed for searching and maintaining feasibility of topology chromosomes. In this research, mutation and recombination operators are developed.

### 6.1.1 Existing operators

The topology chromosome of HVAC configuration is a specially formulated integer string. There are evolutionary operators suitable for integer chromosomes found in other applications. Given the particular requirements of HVAC system topology, however, the existing operators are unlikely to be effective.

#### Classic operators for integer chromosomes

The classic operators for integer chromosomes, such as \(1\)-point and \(n\)-point crossover, and \(flip\) mutation, are in fact searching in the full variation space of the integer string, as the valences rule is not maintained. For example, the \(1\)-point crossover works on the parent chromosomes:

\[
(1 \ 2 \ 3 \ 4 \ | \ 5 \ 6 \ 7 \ 8) \text{ and } (3 \ 7 \ 5 \ 1 \ | \ 6 \ 8 \ 2 \ 4)
\]

The cut point is randomly chosen at, for instance, between fourth and fifth genes. Each child chromosome takes a piece from both of the parents, therefore:

\[
(1 \ 2 \ 3 \ 4 \ 6 \ 8 \ 2 \ 4) \text{ and } (3 \ 7 \ 5 \ 1 \ 5 \ 6 \ 7 \ 8)
\]
Both of the children are illegal according to the valences rule, which requires complete set of number 1 to 8 to be present in the encoding. 5 and 7 are missing in the first child, whereas 2 and 4 are missing in the second. The n-point crossover, which cuts the parents into more than 2 pieces to mix, and the flip mutation, which randomly replaces a gene with a randomly chosen number, has the similar property. These operators are highly destructive and tend to produce illegal topology encodings; thus are not recommended for this application.

Initialization and randomization

The topology chromosomes that comply with the valences rule can be created with special initialization method. The set of gene values in the topology chromosome has to be determined before the string is assembled. As a result, the topology chromosomes vary only in sequences of the same set of values. The set of gene values is decided by the indexes of the components. Consider a configuration including the following components:

DIV(0) - MIX(1) - COOL(2) - HEAT(3) - ZONE(4) - AMBIENT(5)

The numbers in the brackets behind each component are their indexes. The initial set of gene values is (0 1 1 2 3 4 5). Note that there are 2 “1”s representing the two input ports on MIX(1). When a topology chromosome is created, it first copies the default string to its genes. Then the gene string is shuffled for sufficient times to achieve a random sequence. This algorithm is also used in randomize mutation operator.

Mutation

The “Swap Links mutation” (LINK) is based on the generic swap-type mutation that invereses the position of two randomly selected genes. As only the sequence of genes is changed as the result of mutation, the mutant complies with the valences rule, as does the original chromosome. For a topology chromosome, inversion of the integers representing the “To” links effectively exchanges two branches in the network, as illustrated in Figure 6-1. The number of swaps to be performed can be specified as a parameter of the operator.
As shown in the example, the result topology after mutation is no longer strongly connected. There is only one directed link between section \((5 1 3 2)\) and section \((0 4)\), therefore air cannot circulate between the two sections. The *Swap Links mutation* operator cannot preserve strong connectivity of the topologies; thus it is also destructive to the feasible topologies.

**Crossover**

The *partially-mapped crossover* operator (PMX) was introduced by Goldberg and Lingle [Gol85] to tackle the travelling salesman problem (TSP). Although the TSP is different optimisation problem, it is similar to the topology problem in the graph properties - the encoding of a "tour" (solution) in TSP is also a sequence of predefined integer numbers. In this case, the PMX algorithm is suitable for preserving the satisfaction of valences rule in topology search. Given two parent strings, the algorithm of PMX can be summarized as "a portion of one parent string is mapped onto a portion of the other parent string and the remaining information is exchanged."

Consider two parent strings \((1 2 3 4 5 6 7 0)\) and \((3 7 5 1 6 0 2 4)\)

Two cut points along the strings are selected at random. Suppose that the first cut point is selected between the third and the fourth gene, and the second one between the sixth and the seventh gene.

Parent A: \((1 2 3 4 5 6 7 0)\)

Parent B: \((3 7 5 1 6 0 2 4)\)
The substrings between the cut points are called the mapping chapters. The mappings $4 \leftrightarrow 1$, $5 \leftrightarrow 6$, and $6 \leftrightarrow 0$ are defined between the chapters. The mapping chapter of the Parent A is thus copied into the Child B, and the mapping chapter of the Parent B is copied into the Child A.

Child A: (xxx | 1 6 0 | xxx)

Child B: (xxx | 4 5 6 | xxx)

The algorithm tries to fill the vacant genes in the children by copying the gene values from the corresponding parent, i.e. Child A copies from Parent A, and Child B copies from Parent B. In case a gene value is already present in the child, it is replaced according to the mappings. For example, the first gene of Child A tries to copy the Parent A’s first gene value, which is a “1”. However, there is already a 1 present in Child A. The first gene of Child A is thus filled with “4” because of the mapping 1 \leftrightarrow 4. The second, third and seventh genes of Child A can be taken from the Parent A. The last Gene of Child A is filled with “5”, instead of “0”, because of the mappings 0 \leftrightarrow 6 and 6 \leftrightarrow 5.

Child A: (4 2 3 | 1 6 0 | 7 5)

Similarly,

Child B: (3 7 0 | 4 5 6 | 2 1)

Figure 6-2 shows part of the result produced by the PMX operator. From Parent A to Child B, part of the topology is preserved. However, the PMX operator has a disadvantage similar to that of the LINK operator. It tends to be destructive because it does not preserve connectivity.
6.1.2 New topology operators

Though there are operators available for maintaining legal encoding of graphs as required by topology synthesis, new operators are required to preserve the connectivity of established topology chromosomes.

Swap components mutation

The new topology mutation operator, "Swap Components mutation" (POS), is illustrated in Figure 6-3. The positions of component <2> and component <0> in the network are exchanged by sequentially swapping the "To" and "From" links belonging to each component. If either component had had more than one "To" or "From" link, graph based analysis would have been applied to determine which link can be swapped to ensure preservation of the network connectivity. The advantage of this operator is that if a topology has already satisfied, the connectivity requirement, further operations do not generate topologies that violate it. The POS operator generates fewer infeasible solutions than the LINK operator, but it is weaker at exploring new topologies.

![Figure 6-3 Illustration of Swap Components mutation operator](image)

Adjacent component crossover

The objective of crossover operators is to combine the features of existing chromosomes and produce new chromosomes. It can usually be realized by preserving features from one parent in the child, while incorporating features from the other parent as well.

A new topology recombination operator, "Adjacent Components crossover" (ADJ), has been implemented in order to enhance both connectivity and propagation of features. The procedure is based on the assumption that the adjacency of specific components is a useful feature for an HVAC configuration. The ADJ operator performs minimal relocation of components in the clone of one parent, so as to make the pair of adjacent components in the
other parent, adjacent in the child also. The procedure is illustrated in Figure 6-4. Firstly, the parent chromosomes are cloned and following steps performed:

1. A component that is present in both topologies is selected at random as the base component (component $<1>$ in this instance).

2. The component next to the base component is identified in both topologies respectively. If this component is same in both topologies, or if it is absent from either topology, restart from step 1. The feature of parent A identified in this example, is the adjacency of $<1> \rightarrow <3>$, whereas the feature of parent B is the adjacency of $<1> \rightarrow <2>$.

3. The algorithm that exchanges components in the POS operator is used to swap components in parent A in the example. This ensures the preservation of connectivity in the child $A'$. So for parent A, these operations are; where $<3>$ is linked from $<1>$, swap $<3>$ with $<2>$ so that $<1>$ and $<2>$ become adjacent.

4. Step 3 is then repeated for parent B to achieve the adjacency feature ($<1> \rightarrow <3>$) in parent A.

![Figure 6-4 Illustration of Adjacent Components crossover](image)

The result of these operations is that each child preserves most of the network structure from one of the parents, while acquiring a new feature from the other parent. In this way, if the parent topologies are both strongly connected, the children they produce are strongly connected, too. From parent to child, however, only the position of one component is
changed. The children topologies tend to be similar to their parents. Therefore, similar to the POS operator, the ADJ operator also lacks power of topology exploration.

### 6.1.3 Evaluation of the topology operators

Two tests have been performed to evaluate the effectiveness of the new operators. In the first test, the operators are used to produce new individuals from manually selected populations. The proportion of feasible topologies in the children produced by different operators from the initial population is compared. This provides a measure of the probability at which an operator will produce feasible topologies from an existing topology chromosome.

Two initial topology populations are prepared, both based on a set of 15 components. The topologies in the first population are randomly initialized; whereas the second initial population contains only feasible topology chromosomes according to the topological constraints for HVAC configuration. The feasible topologies are generated at random and tested for feasibility a priori. The operator under test continually selects individuals from the initial population, producing new individuals, until 10,000 new chromosomes have been produced. The same test is repeated on a given operator 20 times. The mean and standard deviation of the results are given in Table 6-1.

<table>
<thead>
<tr>
<th>Mutation</th>
<th>From Random Mean (stdev)</th>
<th>From Feasible Mean (stdev)</th>
<th>Crossover</th>
<th>From Random Mean (stdev)</th>
<th>From Feasible Mean (stdev)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAND</td>
<td>99.1(12.0)</td>
<td>100.0(11.1)</td>
<td>NPoint</td>
<td>0.9 (1.04)</td>
<td>118.7 (19.0)</td>
</tr>
<tr>
<td>LINK</td>
<td>102.9 (20.0)</td>
<td>2439.7 (30.3)</td>
<td>PMX</td>
<td>95.9 (8.6)</td>
<td>641.0 (19.4)</td>
</tr>
<tr>
<td>POS</td>
<td>141.3 (28.6)</td>
<td>6326.6 (35.7)</td>
<td>ADJ</td>
<td>132.6 (24.1)</td>
<td>6221.2 (51.3)</td>
</tr>
</tbody>
</table>

The topology-specific operators (POS and ADJ) are compared with Random mutation (RAND), Swap link mutation (LINK), N-point crossover (NPoint), and the Partially Matched crossover (PMX). Results shown in Table 6-1 demonstrates that the number of feasible solutions generated by the topology-specific operators is significantly higher than that of the conventional operators. Both POS mutation and ADJ crossover have more than 60% probability of producing new feasible topologies from feasible parents. Note that the results from
the random mutation are around 1.0% for both random and feasible initial populations. This gives a measure of the proportion of feasible topologies within the search space. Any operator that achieves a “feasible-from-feasible” probability higher than 1.0% is likely to perform better than a random search.

The second test for the topology operators evaluates the dynamic performance of convergence. Since the topology search problem and the operation optimisation problem for configuration synthesis are interrelated, it is possible to search for a topology that works with a set of predefined operations, as well as to optimize the operations for a particular topology. With operation variables fixed, the search of optimal topology provides a way to evaluate the performance of the topology-related algorithms.

The procedure of the test is as follows. First, a conventional dual-duct configuration for the 2-zone HVAC system (Chapter 3, Figure 3-1) is selected. The operation of the selected configuration, including the component duties and air flow rates in the system, are optimized. The second step is to set up the configuration optimisation problem, in which the duties and flow rates are fixed. The optimal configuration in this case must be the original configuration and hence convergence on this solution can be used as a measure of operator performance.

Combinations of different topology operators are used in each trial. The “Hyper” crossover operator comprises 90% of ADJ and 10% of PMX operators. This means when the Hyper crossover is called, it has a 90% chance to behave like an ADJ, whereas the other 10% of the time, it behaves like a PMX. The Hyper mutation operator is composed of 62.5% of POS, 31.25% of LINK, and 6.25% of RAND.

Figure 6-5 illustrates the average rate of convergence for various operators as a result of 30 runs. The vertical axis shows a measure of closeness of the best solution to the optimum topology, the dual-duct configuration in this case. Clearly, the evolutions using N-point crossover and PMX crossover show inferior performance than those using topology-specific operators. While the Adjacent Components crossover showed significant advantage in terms of convergence, the hyper operator design has a balanced performance in both convergence and exploration (see Figure 6-6).

The topology exploration performance is measured by the number of different topologies that have been traversed during the search. The more topologies explored, the higher the chance to find the global optimal solution. Figure 6-6 shows the exploration power of each operator combinations. The Hyper crossover-Hyper mutation design showed strong explora-
tion performance. It performs only second to the \textit{N-point-Random} combination, which roughly represents a random search.

Figure 6-5 Effectiveness of evolutionary operators in searching a specified topology

Figure 6-6 Exploration power of the topology operators
6.2 Reproduction operators for Operation chromosomes

The operation chromosomes for HVAC configuration are a set of real-encoded chromosomes that represent the operation set points under the design conditions. Since the operations of the HVAC system under each design condition are independent of each other, each of the operation chromosomes can be handled individually. A number of crossover and mutation operators have been adapted for the operation chromosomes in this research. Their performances are evaluated in this section.

6.2.1 Definitions of Operation chromosome operators

Selective Duties crossover

As each Operation chromosome in the configuration genome represents the set points for the operation of the configuration in one design condition, they are independent to each other. During the search, some of the Operation chromosomes in a solution may have been optimized, while others are not. The fitness of the solution, however, is evaluated as whole, with the qualities of all Operation chromosomes taken into account. The few high quality Operation chromosomes may be overshadowed by other chromosomes. The Selective Duties Crossover tackles such problem by inspecting the quality of each individual Operation chromosome, and preserving the best ones.

When two configuration solutions in the current population are selected to be recombined, the Selective Duties crossover compares the infeasibility and objective information on individual Operation chromosomes, and selects the better quality chromosomes from both parents to put into the child solution. Consequently, the Operation chromosomes in the child genome have better or equal fitness as the parents.

List 6-1 gives the algorithm of the Selective Duties Crossover. This crossover only performs on the two parent genomes that have identical ComponentSet and Topology chromosomes. For each pair of Operation chromosomes from the parents, the infeasibility information is first compared. The chromosome with lower infeasibility mark will be selected and put into the child genome. If the infeasibility scores are same, the objective scores of the two chromosomes are compared. Again, the chromosome with lower objective score will be inherited by the child.
### List 6-1 Pseudo-code of Selective Duties Crossover

#### Centre of Gravity (CoG) crossover

The Centre of Gravity (CoG) crossover is introduced by Angelov [Ang01]. It is an adaptive operator that, like Selective Duties Crossover, uses evaluation information of the Operation chromosomes during the process. Unlike the Selective Duties Crossover, however, the CoG crossover works on the genes, instead of chromosomes. Each gene of the child chromosome is calculated from the parents' genes with their infeasibility scores. Consider 2 parent Operation chromosomes A and B, their evaluation scores are $X_A$ and $X_B$, and the genes are denoted as $G_{AI}$ and $G_{BI}$. The gene values of Child C and Child D are calculated by,

**Child C:**

$$G_{CI} = \frac{G_{AI} \cdot X_A + G_{BI} \cdot X_B}{X_A + X_B} = G_{AI} + \frac{(G_{BI} - G_{AI})X_B}{(X_A + X_B)} \tag{6-1}$$

**Child D:**

$$G_{DI} = G_{AI} - \frac{(G_{BI} - G_{AI})X_B}{X_A + X_B} \tag{6-2}$$

The genes of Child A and Child B are located on either side of the gene from the better parent chromosome. The closeness of the child genes to the better parent is calculated by the relative quality of the two parents. Figure 6-7 illustrates the assumption of the CoG operator. For a continuous evaluation function, if the two parents are located on one slope, the extrapolated child may be closer to the pinnacle than both parents; otherwise, if the parents are on the opposite sides of the pinnacle, the interpolated child may be closer to the optimum.
In this research, only infeasibility scores of the Operation chromosomes are taken into account. As a result, the CoG crossover is biased to minimizing infeasibility, rather than the objective.

Blend crossover and Arithmetic crossover

Blend crossover and Arithmetic crossover are common operators for real-encoded chromosomes. The Blend crossover chooses child chromosome from the boxy area defined by the parent chromosomes. Consider a 2-dimensional example: the two parents define the opposite corners of the rectangular area. The child chromosome is chosen randomly from the area with uniform distribution (see Figure 6-8).
Arithmetic crossover is similar to the CoG crossover, except the weights of the parents are determined by a user-supplied parameter. Figure 6-9 illustrates a 2-dimensional example.

Each gene of the child is calculated using the following equation,

\[ G_{\text{child}_i} = \text{gaussian}(G_{A_i} \cdot F + G_{B_i} \cdot (1 - F), \text{Stdev}) \]  

(6-3)

Where \( F \) is an arbitrary weighting parameter in the range of \([0, 1]\). It is common to use a Gaussian random number generator to make the Arithmetic Crossover less deterministic. The \text{Stdev} in the equation is the standard deviation of the Gaussian distribution.

Random mutator and Shift Duty mutator

A Random mutator chooses new gene values randomly according to uniform distribution in the possible range of gene values (Figure 6-10).

The Shift Duty mutator is a variation of Gaussian mutation operator. The new gene value is chosen according to Gaussian distribution around the current gene value. The shape of the probability distribution is determined by a user-specified standard deviation. Gaussian mutation is normally less disruptive than the Random mutation.
The Reductive mutation operator is developed to assist the optimisation regarding the control set points for the configurations. The objective of the optimisation is to minimize the energy consumption of the configuration, which normally means the minimization of airflow in the system and energy consumed by each component. An evolutionary operator that can guide the optimisation towards reduction of flow and duties would be helpful. The Reductive mutator is deliberately reducing each of the Flow gene values by a small fraction, and removing duties on randomly picked components. The effectiveness of the Reductive mutator, together with other Operation chromosome operators, is evaluated in the next section.
Chapter 6 Problem-specific algorithm operators

Hyper crossover and Hyper mutator

Different operation chromosome operators are combined into “Hyper” operators. The “Hyper” crossover operator comprises 25% of CoG crossover, 60% of Arithmetic crossover, 10% of Blend crossover, and 5% of N-point crossover. The Selective Duties crossover can also be applied before recombining individual operation chromosomes. The Hyper mutation operator is composed of 50% of Shift Duty mutation, 25% of Random mutation, and 25% of Reductive mutation. The balances between different operators are chosen arbitrarily, as a result of a number of trial optimisations. However, further study is required to develop optimal composition of the Hyper operators.

6.2.2 Evaluation of the operators

A test problem has been set up to evaluate the effectiveness of the operators for Operation chromosomes. The Dual-duct HVAC system configuration (Chapter 3, Figure 3-1) is used. The ComponentSet and Topology chromosomes of the configuration are fixed. The Operation chromosomes are optimised under 9 design conditions. For each combination of operators, 30 trial optimisations are performed to calculate the average convergence rate. In total, 8 sets of Operation chromosome operators have been tested. They are:

Op1 – N-Point real chromosome crossover and Random mutator
Op2 – Blend crossover and Random mutator
Op3 – Arithmetic crossover and Random mutator
Op4 – CoG crossover and Random mutator
Op5 – Hyper crossover (without Selective Duties crossover) and Random mutator
Op6 – Hyper crossover (without Selective Duties crossover) and (Random + Shift-Duty) mutator
Op7 – Hyper crossover (without Selective Duties crossover) and Hyper mutator
Op8 – The present setting of Hyper crossover and Hyper Mutator

Figure 6-12 and Figure 6-13 show the convergence of infeasibility and objective, respectively. In terms of infeasibility convergence, the CoG crossover – Random mutation combi-
nation (Op4) showed superior performance. When the performance of objective convergence is concerned, however, Op4 was among the worst. This is because the weights in the CoG crossover are calculated from infeasibility scores only; therefore the operator is more concentrating on minimizing infeasibility, rather than objective. It is evident that, for a constrained problem like optimisation of HVAC configuration operations, balanced effort has to be maintained between minimizing infeasibility and objective. Bias towards either of the targets may hinder the overall performance.

![Graph with data points and lines representing different operators]

**Figure 6-12 Performance of Operation chromosome operators – infeasibility convergence**

When used on their own, the classic real chromosome operators such as N-Point, Blend, Arithmetic crossovers, and Random mutation, are clearly showing the worst performance in infeasibility convergence. The Hyper crossover – hyper mutation set up showed the best balanced performance in minimizing both infeasibility and objective. Studying the relations between each line for Op5 to Op8, it can also be concluded that: the Shift Duty mutation (Op5 – Op6) has little impact on performance in terms of both infeasibility and objective; the use of reductive mutation operator (Op6 – Op7), on the other hand, significantly improve the performance as shown in both figures; the search performance has been further enhanced with the use of Selective Duties crossover (Op7 – Op8).
Figure 6-13 Performance of Operation chromosome operators – objective convergence

It is worth to note that, while the solutions are infeasible, their objective scores could be misleading. Therefore the convergence lines for Op1, Op2, and Op3 do not convey much information.

6.3 "Ageing" operator

In this research, a dynamic sharing method has been developed. The purpose of the Ageing operator is to maintain the diversity of families, as well as the appropriate size of the family of the promising configuration. The definition of family, and the need for it, has been discussed in Chapter 5, 5.1.4.

Figure 6-14 shows the characteristic behaviour of the EA without sharing in the search of optimal HVAC configurations. Due to the fact that the optimization problem is highly constrained and multi-modal, when a feasible topology is found and its operation is partially optimized, it will receive an outstanding fitness score comparing to other solutions in the same population. This makes it very difficult for other solutions to compete with the dominant one for survival. The example shows the EA search with population size of 1,000 solutions, running up to 10,000 generations. Each dot in the chart represents one unique topology that has been explored. The X axis is the generation number when the topology is first discovered. The Y axis is the total number of evaluations has been performed on the
solutions having the topology. The dominant topology in the example first appeared at about 1,200th generation. Between the 1,200th and 10,000th generation, a total of more than 7,000,000 solutions of the same topology are evaluated, which means in each population of 1,000 solutions, there are about 800 of them sharing this topology. In this case, the operations of other topologies have very little chance to be optimized.

![Figure 6-14 Number of evaluations of the explored topologies](image)

### 6.3.1 Sharing

One approach to tackle the premature convergence on one topology is to use sharing techniques. Goldberg and Richardson [Go187] defined the most commonly used sharing scheme. The technique they described used a sharing function to penalise an individual’s fitness, depending on the proximity of other individuals. The sharing function is defined as Equation 6-4.

\[
S(d_{ij}) = \begin{cases} 
1 - \left( \frac{d_{ij}}{\sigma} \right)^a, & \text{if } (d < \sigma) \\
0, & \text{otherwise}
\end{cases}
\]  

(6-4)

Where,

\(d_{ij}\) is the distance measured between the individual \(i\) and \(j\)
Chapter 6 Problem-specific algorithm operators

\[ \sigma \] is the threshold parameter

\[ \alpha \] is the factor for the power law sharing function

For a minimisation problem, the new fitness value adjusted by the sharing function is calculated by Equation 6-5.

\[
(f_i') = f_i \cdot \left( \sum_{j=1}^{N} S(d_{ij}) \right)
\]  \hspace{1cm} (6-5)

Where,

\[ f_i \] is the fitness value of the individual \( i \)

\[ N \] is the number of individuals in the population

Note that in Equation 6-4, \( S(d_{ij}) \equiv 1 \), \( \sum_{j=1}^{N} S(d_{ij}) \geq 1 \), \( f_i' \geq f_i \).

For the configuration problem, the approximation of two configurations can be defined on the family boundary. The sharing function and new fitness can be simplified to:

\[
S(d_{ij}) = \begin{cases} 
1, & \text{if in the same family} \\
0, & \text{otherwise}
\end{cases}
\]  \hspace{1cm} (6-6)

\[
(f_i') = f_i \cdot \left( \sum_{j=1}^{N} S(d_{ij}) \right) = f_i \cdot M_i
\]  \hspace{1cm} (6-7)

Where,

\[ M_i \] is the size of the solution family of the individual \( i \)

This scheme requires each and every individual in the population to belong to a different family, to avoid being penalised by the sharing function. In order to optimise the operation for a configuration, however, suitable family size is required to allow evolution within the family. Therefore an attenuated, and preferably, dynamic strategy is required.

6.3.2 Definition of ageing operator

There are two objectives for the development of new sharing method: to avoid dominance of a single topology and encourage exploration; and to allow operation (control set points) of a promising configuration being optimised.
The Ageing operator is designed to break the dominance of certain topology along the progress of evolution. The exploration of topologies is tracked with a history record. This information is used as a dynamic factor to modify the fitness score for each solution. The “age” of a topology is defined as the total number of evaluated individuals that have this topology. A parameter is specified as a quota for each topology in each generation. The unused quota is transferable to the following generations. For example, let the quota factor \( Q = 20 \), if a topology first appears in generation 3, there is an initial quota of 60 individuals for this topology. Assume that there are 3 individuals having the given topology in the current generation, the quota for the next generation will be 77. If the number of individuals in the next population exceeds 77, a penalty is applied to each and every solution having the same topology in the population.

The definition of the Ageing operator is described in the following equation:

\[
 f_i' = f_i \cdot \max \left( (M_{\text{eval}_i} - Q \cdot N_{\text{gen}}), 1 \right)
\]  

(6-8)

Where,

- \( f_i, f_i' \) are the original and modified fitness of solution \( i \)
- \( Q \) is the quota for each generation
- \( M_{\text{eval}_i} \) is the total number of evaluated individuals having the topology
- \( N_{\text{gen}} \) is the present generation number

Note that when \( M_{\text{eval}_i} \leq (Q \cdot N_{\text{gen}} + 1) \), \( f_i' = f_i \).

Since Stochastic Ranking is used for constraint handling in the present approach, the fitness score of each solution in the population is its rank. The solution ranks are zero-based; therefore the best solution in the population has a rank of “0”. As a result, the ageing operator does not affect the status of the best solution in any case, even though ranks of other individuals in its family may be penalized by their age. This is useful for maintaining the best solution in the population.

6.3.3 Effectiveness of the ageing operator

The effectiveness of the Ageing operator is evident. Figure 6-15 shows the topology exploration map of the evolutionary process with the ageing operator. The dotted line on the chart is \( M_{\text{eval}} = 20 \cdot N_{\text{gen}} \). The dots scattering above the line are the topologies that were
once the best solutions, and whose family dominated the population. Three types of growth of the families were observed. The first type is gradual growth, such that happened with the family of topology A. The family size was relatively stable, and occupied a small portion of each population.

![Figure 6-15 Number of evaluations of the explored topologies, with Ageing operator](image)

The second type of growth is more common, such as with topology B. Soon after it was discovered, and appeared to be a good configuration, the family of topology B quickly gained popularity due to the large initial quota. A large number of evaluations have been performed to optimize the operation of the topology. When the total number of evaluations met with the $M_{eval} = 20 \cdot N_{gen}$ line, the ageing operator kicked in and started penalizing the over-sized family. The progress of the topology was slowed and finally its dominance was replaced by new topologies.

The development of the family of topology C represents the third growth type. Like topology B, C was discovered late in the evolution, and started to dominate the search quickly. Unlike B, however, C did not cease to exist after its growth hit the $M_{eval} = 20 \cdot N_{gen}$ line. Instead, it kept developing along the ageing line. The Ageing operator limited its family size to about 20. This was because topology C was the optimum found the optimisation. It had
not been out-performed by any other topology, therefore stayed on the top of each population.

Comparing to Figure 6-14, where one topology dominated the population from very early stage of the evolution to the end, the ageing operator forced more topologies to be explored and optimized.

Figure 6-16 shows the periodical fluctuation of the number of unique topologies in the population along the progress of generation. The green line is the number of all topologies, whereas the blue line is the number of new topologies that have not been discovered before this generation. Each surge of the variety of topologies occurs when the ageing operator is suppressing the dominant family, in which case the new and minority topologies receive preferable ranks comparing to the old family members. The surge settles down when a "new" outstanding topology is identified, and its family starts to dominate the population.

![Figure 6-16 Change of number of topologies with generations](image)

Although it is clear to see that Ageing operator dramatically changes the progress of the evolutionary search, the behaviour and dynamics of the operator deserves further study. Also, the selection of the quota factor may have an impact on the algorithm performance; therefore it should be studied in the future.
6.4 Summary

In this chapter, the development of new operators for the configuration synthesis problem has been described. These operators belong to 3 categories, the topology operators, the Operation operators, and the Ageing operator.

The topology operators are designed for the exploration of the topological space. The topology problem of the configuration synthesis is essentially a graph problem, which is known to be hard to solve. The two key developments, the Swap Components Mutation and the Adjacent Components Crossover, are designed to produce reasonable topologies while maintain the ability to explore. Problem specific operators have also been implemented for the optimisation of Operation variables. Evaluation of these operators showed significant improvement over the generic operators, in terms of convergence speed.

The Ageing operator is specifically developed to tackle premature convergence on single topology during the search. Analysis showed the Ageing operator was able to encourage the emergence of new topologies, by penalizing the dominating topology. Unlike other sharing methods, the Ageing operator is adaptive to the history of evolution. Although further analysis of the behaviour of Ageing is required, a preliminary experiment has shown the effectiveness of the method.

In the next chapter, the configuration synthesis approach is subjected to a number of tests, in order to be validated as a whole.
Chapter 7

Example optimisation: simple systems

In the previous chapters, the optimisation problem for HVAC system configuration synthesis has been established. Evolutionary algorithm has been implemented to tackle the problem. Providing the characteristics of configuration synthesis problems, enhancements have been developed to improve the performance of EA. In this chapter, two example optimisations are performed to validate the approach. The tasks are: (1) synthesis of the basic configuration for single-zone systems under summer operation condition; and (2) synthesis of 2-zone configuration in a situation where free cooling is available throughout the year.

The first example is to validate the ability of the approach in exploring the search space for the global optimum. The result from the search using EA is compared with that from an exhaustive search. The second example is to demonstrate the ability of the approach in synthesising feasible configurations that satisfy multiple operation conditions. The design context is set within a temperate climate where no active heating or cooling is needed throughout the year. The configuration synthesis approach is tested to make full use of free cooling, as well as minimising fan energy consumption. The performance of synthesised configuration is compared with that of the typical single-duct two-zone system.
7.1 Synthesis of the basic single-zone configuration

One of the simplest HVAC systems is the single-zone system with one re-circulation branch and a cooling coil. Five components are present in this system, including the cooling coil (Cool), a mixing tee (Mix), a diverging tee (Div), the conditioned zone (Zone), and the ambient environment (Ambient). For the set of 5 components, it is possible to list all feasible configurations. An exhaustive search for the optimum operation of each configuration can then be performed; and the global optimum configuration can be identified. The optimisation approach developed in previous chapters is validated by synthesising the optimum configuration.

7.1.1 Problem Definition

The configurations for the basic single-zone system are to be tested in one summer design condition. The ambient temperature and relative humidity are 38.9°C and 35.9%, respectively. The design condition of the occupied zone is 20°C / 50%RH, with a sensible load of 5.066kW, a latent load of 0.200kW, and minimum fresh air demand of 0.032kg/s. The optimization objective is to minimize the system energy use, which includes the cooling coil duty and fan energy consumption. The constraints described in Chapter 4, section 4.2 are applicable in this problem. Briefly, they are,

- The supply air temperature and humidity ratio must be within ±0.2 °C and ±0.00075 kg/kg range of the supply air condition required to meet to zone loads;
- The minimum fresh air supply must be greater than or equal to 0.032kg/s;
- The supply air temperature must be in the range 13.0°C - 27.0°C;
- The cooling coil outlet temperature must be greater than or equal to +5°C;
- The range of air mass flow rate in any component other than the zone must be in the range 0.0kg/s to 3.0kg/s;
- The range of air mass flow rate for the zone must be in the range 0.04 kg/s to 1.4 kg/s;
- The connectivity rules for topology
### 7.1.2 Exhaustive search

A fixed ComponentSet of 5 components has 360 possible Topologies. Among these, there are 40 strongly connected topologies. Manual inspection shows 11 topologies are likely to be feasible. These topologies are illustrated in Figure 7-1; their Topology chromosomes are listed in Table 7-1. For each topology, there are two flow rates to be optimized, the exhaust (or fresh) air flow rate (M0), and the flow rate in the recirculation leg (M1). The optimum duty of the cooling coil that conditions the supply air is to be searched, too.

The optimum value of these flow rates and the optimum duty of the cooling coil were found by an exhaustive search on each Topology. The exhaustive search was performed with a discrete increment of 0.0001kg/s for the mass flow rates, and 0.001kW for the coil duty. The optimum Topology is labelled (2) in Figure 7-1 and Table 7-1; the values of the mass flow rates and coil duty for this topology are M0=0.0320kg/s, M1=0.7339 kg/s, and a coil duty Q= -5.600 kW.

![Figure 7-1 Feasible topologies for the basic single-zone system](image-url)
The first group of configurations (Figure 7-1 A) can be considered as a standard system with re-circulation; the differences in configurations arise from the position of the cooling coil. Configuration (2) in Table 7-1 is the optimum configuration. Placing the cooling coil in the re-circulation leg (case 2) allows means the coil handles less air than a “standard” configuration (case 0), and therefore the coil has a lower duty. For case 1, the cooling coil is handling the least amount of air in this group. However, the fresh air rate through the coil must be increased if the outlet air temperature of the coil is to remain feasible (≥ +5°C) while meeting the zone loads; this incurs a higher energy use. Case 3 also uses more energy because some amount of cooled air is exhausted directly to the environment. Cases marked (x) are infeasible in the Operation optimization constraints (placing the cooling coil in the exhaust duct will not provide cooling to the zone).

### Table 7-1 Exhaustive search results

<table>
<thead>
<tr>
<th>Group</th>
<th>Case</th>
<th>Topology</th>
<th>Optimal Operation (M0 M1 Q)</th>
<th>Cooling duty (kW)</th>
<th>Circulation (kW)</th>
<th>Total consumption (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>(0)</td>
<td>(123014)</td>
<td>0.032 0.746 -5.56</td>
<td>5.601</td>
<td>0.054</td>
<td>5.655</td>
</tr>
<tr>
<td></td>
<td>(1)</td>
<td>(131024)</td>
<td>0.320 0.964 -19.37</td>
<td>19.369</td>
<td>0.209</td>
<td>19.578</td>
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<tr>
<td></td>
<td>(2)</td>
<td>(231014)</td>
<td>0.032 0.734 -5.60</td>
<td>5.600</td>
<td>0.091</td>
<td>5.691</td>
</tr>
<tr>
<td></td>
<td>(3)</td>
<td>(130214)</td>
<td>0.032 1.023 -5.71</td>
<td>5.713</td>
<td>0.136</td>
<td>5.849</td>
</tr>
<tr>
<td></td>
<td>(X)</td>
<td>(134012)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>(4)</td>
<td>(320114)</td>
<td>0.033 1.086 -5.71</td>
<td>5.712</td>
<td>0.144</td>
<td>5.856</td>
</tr>
<tr>
<td></td>
<td>(5)</td>
<td>(203114)</td>
<td>0.033 0.756 -5.61</td>
<td>5.608</td>
<td>0.061</td>
<td>5.668</td>
</tr>
<tr>
<td></td>
<td>(6)</td>
<td>(301214)</td>
<td>0.185 0.702 -12.31</td>
<td>12.314</td>
<td>0.049</td>
<td>12.363</td>
</tr>
<tr>
<td></td>
<td>(7)</td>
<td>(301124)</td>
<td>0.422 1.309 -25.57</td>
<td>25.574</td>
<td>0.300</td>
<td>25.874</td>
</tr>
<tr>
<td></td>
<td>(X)</td>
<td>(204113)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>(8)</td>
<td>(231401)</td>
<td>0.701 0.147 -32.32</td>
<td>32.319</td>
<td>0.041</td>
<td>32.360</td>
</tr>
<tr>
<td></td>
<td>(9)</td>
<td>(130421)</td>
<td>Humidity unsatisfied</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>(X)</td>
<td>(134201)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>D</td>
<td>(10)</td>
<td>(143102)</td>
<td>Humidity unsatisfied</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>(11)</td>
<td>(140123)</td>
<td>Humidity unsatisfied</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>(X)</td>
<td>(...)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The second group of configurations (Figure 7-1 B) are based on an alternative re-circulation path, in which some fresh air is drawn from the ambient, and exhausted directly. Therefore the configurations in this group perform slightly worse than their counterparts in the Figure 7-1 A. Finally, cases 8 to 11 (Figure 7-1 C and D) are practically same as a full fresh air system and therefore are sub-optimal in their energy use.

It is clear from the Table 7-1 that the difference in predicted performance for between some configurations (e.g. case 2, 0, 5, and 3) is marginal. The difference is from circulation
cost, rather than cooling duty. These configurations form a "neighbourhood", whose impact will be further discussed in the next chapter.

7.1.3 Optimisation results

The Evolutionary Algorithm is set up with a population size of 50 individuals. By the end of each generation, 2 best solutions are copied to the next population; whereas the other 48 solutions are produced by the reproduction operators. The Ageing factor is set to 10 for this problem.

EAs are stochastic optimizers. Their behaviour is normally evaluated through multiple runs of the algorithm. 6 different runs of the ACG have been performed in this test. The number of generations was also varied to test the optimality of the solution. The chance of finding the global optimum increases with the number of generations, although in the rate of convergence is generally exponential, with any improvement slowing as the generations' progress. Table 7-2 indicates that in the 4 runs that are longer than 500 generations, the same optimum configuration was identified (configuration 2 in Figure 7-1).

Table 7-2 Consistency of the optimisation results

<table>
<thead>
<tr>
<th>Generation</th>
<th>Number of evaluations (approx)</th>
<th>Best topology</th>
<th>Best Operation</th>
<th>Objective (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>10,000</td>
<td>1 3 1 0 2 4</td>
<td>0.573 0.477 -20.483</td>
<td>29.8071</td>
</tr>
<tr>
<td>200</td>
<td>20,000</td>
<td>1 3 1 0 2 4</td>
<td>0.462 0.257 -23.451</td>
<td>23.4908</td>
</tr>
<tr>
<td>500</td>
<td>50,000</td>
<td>2 3 1 0 1 4</td>
<td>0.125 0.561 -8.888</td>
<td>8.92418</td>
</tr>
<tr>
<td>1000</td>
<td>100,000</td>
<td>2 3 1 0 1 4</td>
<td>0.032 0.876 -5.813</td>
<td>5.66312</td>
</tr>
<tr>
<td>2000</td>
<td>200,000</td>
<td>2 3 1 0 1 4</td>
<td>0.032 0.715 -5.804</td>
<td>5.66187</td>
</tr>
<tr>
<td>5000</td>
<td>500,000</td>
<td>2 3 1 0 1 4</td>
<td>0.032 0.728 -5.801</td>
<td>5.66151</td>
</tr>
<tr>
<td>Exhaustive</td>
<td>1.12E+10 per topology</td>
<td>2 3 1 0 1 4</td>
<td>0.032 0.734 -5.800</td>
<td>5.66148</td>
</tr>
</tbody>
</table>

Note that the number of function evaluations used by the EA approach, although large, is still significantly lower than the number of function evaluations required to perform an exhaustive search for just a single configuration.

Table 7-3 illustrates a ranking of solutions taken from the final population (generation 5,000) in the 6th run. The position column corresponds to a ranking of the solutions (in a population of 50). Note that 9 out of 11 feasible configurations are present in the final population. Operations of the top 5 configurations identified in the Table 7-1 (case 0, 2, 3, 4, and
5) have been reasonably optimised, too. This proves the ability of the EA approach in finding global optimum solutions for a relatively simple problem.

<table>
<thead>
<tr>
<th>Rank from exhaustive search</th>
<th>Topology ID</th>
<th>Chromosome</th>
<th>Best operation (kW)</th>
<th>Best rank</th>
<th>Number of instances</th>
<th>Best objective (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(2)</td>
<td>(2 3 1 0 1 4)</td>
<td>5.85146</td>
<td>1</td>
<td>10</td>
<td>5.85151</td>
</tr>
<tr>
<td>2</td>
<td>(0)</td>
<td>(1 2 3 0 1 4)</td>
<td>5.65546</td>
<td>7</td>
<td>10</td>
<td>5.71122</td>
</tr>
<tr>
<td>3</td>
<td>(5)</td>
<td>(2 0 3 1 1 4)</td>
<td>5.65733</td>
<td>13</td>
<td>10</td>
<td>5.83446</td>
</tr>
<tr>
<td>4</td>
<td>(3)</td>
<td>(1 3 0 2 1 4)</td>
<td>5.84874</td>
<td>32</td>
<td>8</td>
<td>(Infeasible)</td>
</tr>
<tr>
<td>5</td>
<td>(4)</td>
<td>(3 2 0 1 1 4)</td>
<td>5.85602</td>
<td>30</td>
<td>5</td>
<td>(Infeasible)</td>
</tr>
<tr>
<td>6</td>
<td>(8)</td>
<td>(3 0 1 2 1 4)</td>
<td>12.36321</td>
<td>41</td>
<td>1</td>
<td>(Infeasible)</td>
</tr>
<tr>
<td>7</td>
<td>(1)</td>
<td>(1 3 1 0 2 4)</td>
<td>19.57751</td>
<td>-</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>(7)</td>
<td>(3 0 1 1 2 4)</td>
<td>25.87407</td>
<td>-</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>(8)</td>
<td>(2 3 1 4 0 1)</td>
<td>32.36026</td>
<td>-</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>(9)</td>
<td>(1 3 0 4 2 1)</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>(10)</td>
<td>(1 4 3 1 0 2)</td>
<td>-</td>
<td>46</td>
<td>1</td>
<td>(Infeasible)</td>
</tr>
<tr>
<td>12</td>
<td>(11)</td>
<td>(1 4 0 1 2 3)</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>13</td>
<td>(X)</td>
<td>(... ...)</td>
<td>-</td>
<td>45</td>
<td>6</td>
<td>(Infeasible)</td>
</tr>
</tbody>
</table>

### 7.1.4 Conclusion

The synthesis of a minimalist configuration shows that the present EA-based approach performs well compared to exhaustive search. The solutions successfully converged to the global optimum in less than 100,000 evaluations, whereas the exhaustive search performed $10^{10}$ evaluations on each topology.

However, the basic single-zone configuration synthesis is a very simple problem, where there are only 9 variables in total (6 for topology, and 3 for operation). For a normal 2-zoned HVAC configuration with a set of 9 typical operation conditions, the number of variables increases to over 100. The performance of the approach will be validated in the next section.

### 7.2 Configuration synthesis for low load building

The second test is based on a 2-zone system containing the following set of components: 2 heating coils, 2 cooling coils, 2 humidifiers, 4 DIVs and MIXs, Ambient and 2 zones. This component set gives a total of 120 problem variables, 21 discrete variables for the configuration topology, and 99 continuous variables for the system operations. There is one topology
variable for the outlet connection of each component, including one for the ambient condition and the two zones; diverging tees have two outlets and therefore there are two variables associated with DIVs. There are 9 load conditions, and for each load condition, the problem variables are the capacity of the coils and humidifiers (6 variables), and 5 air flow rates (one for each mixing tee and one for the outside air entering the system).

The purpose of the validation is to test the following abilities of the approach:

- Minimize energy consumption by optimizing the operation of configuration
- Identify redundant air-handling components
- Minimize fan energy by relocating components in the configuration

7.2.1 Problem definition

The test problem assumes the low load building is located in a region where climate is mild, such as San Francisco, California, USA. For most of the conditions throughout the year, free cooling alone can satisfy the air-conditioning demands. The evolutionary algorithm developed for configuration synthesis is expected to eliminate the use of active heating, cooling, or humidification. The only source of energy consumption should be circulation (fan consumption). The algorithm is also expected to move the redundant coils and humidifiers to the location where airflow is less restricted.

<table>
<thead>
<tr>
<th>Data Point</th>
<th>Ambient Condition</th>
<th>East</th>
<th>West</th>
<th>Total heat gain</th>
<th>Minimal fresh air load</th>
<th>Zone Load Residual after free cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time of day</td>
<td>Time of day</td>
<td>Ta (°C)</td>
<td>w (kg/kg)</td>
<td>L_e (kW)</td>
<td>L_i (kW)</td>
<td>L_e (kW)</td>
</tr>
<tr>
<td>Summer</td>
<td>06:00</td>
<td>19.1</td>
<td>0.0064</td>
<td>1.910</td>
<td>0.080</td>
<td>0.759</td>
</tr>
<tr>
<td></td>
<td>14:00</td>
<td>19.8</td>
<td>0.0075</td>
<td>0.622</td>
<td>0.080</td>
<td>1.937</td>
</tr>
<tr>
<td></td>
<td>17:00</td>
<td>17.8</td>
<td>0.0077</td>
<td>0.080</td>
<td>0.080</td>
<td>1.945</td>
</tr>
<tr>
<td>Winter</td>
<td>06:00</td>
<td>7.8</td>
<td>0.0056</td>
<td>0.861</td>
<td>0.080</td>
<td>0.461</td>
</tr>
<tr>
<td></td>
<td>14:00</td>
<td>12.2</td>
<td>0.0063</td>
<td>0.727</td>
<td>0.080</td>
<td>0.868</td>
</tr>
<tr>
<td></td>
<td>17:00</td>
<td>10.8</td>
<td>0.0068</td>
<td>0.411</td>
<td>0.080</td>
<td>0.422</td>
</tr>
<tr>
<td>Spring/Fall</td>
<td>06:00</td>
<td>11.1</td>
<td>0.0049</td>
<td>1.244</td>
<td>0.080</td>
<td>0.695</td>
</tr>
<tr>
<td></td>
<td>14:00</td>
<td>17.2</td>
<td>0.0068</td>
<td>1.170</td>
<td>0.080</td>
<td>1.531</td>
</tr>
<tr>
<td></td>
<td>17:00</td>
<td>14.4</td>
<td>0.0064</td>
<td>0.850</td>
<td>0.080</td>
<td>0.704</td>
</tr>
</tbody>
</table>
The weather conditions and design loads for this example are listed in Table 7-4. Throughout the year there are positive heat gains in the zones, while the ambient temperature is normally lower than the zone temperature settings. As a result, the zone loads should be able to be met by the outside air supply. No active heating or cooling would be needed.

7.2.2 Benchmark configuration

A typical configuration, the single-duct VAV system (Figure 7-2), is used as the reference configuration for the test in free cooling conditions. The operation of the single-duct configuration is optimised; therefore the optimal flow rates and duties are derived for each load condition.

Table 7-5 shows the optimal performance of the single-duct configuration in the design conditions. The coils and humidifiers are turned off in all conditions. The energy consumption is from the fans that circulate the air in the system. The air flow rates in different branches in the system are annotated in Figure 7-2. The first recirculation leg is almost switched off all the time. Most of the recirculation is via the second leg, in which there are fewer components that blocks the air flow. However, the air-handling components in this configuration are in the path of outside air supply, or on the supply side of the zones. This results in unwanted restriction to the air flow, which means excess fan energy is consumed.
Table 7-5 Performance of single duct VAV configuration in free cooling conditions

<table>
<thead>
<tr>
<th>Data points</th>
<th>Total Fresh Air (kg/s)</th>
<th>Total Circulated Air (kg/s)</th>
<th>Total Pressure Loss (Pa)</th>
<th>Total Circulation Consumption (kW)</th>
<th>Total Heating and Cooling Duty (kW)</th>
<th>Total Energy consumption (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>08:00</td>
<td>0.860</td>
<td>0.860</td>
<td>128.4</td>
<td>0.150</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>14:00</td>
<td>1.144</td>
<td>1.157</td>
<td>230.1</td>
<td>0.361</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>17:00</td>
<td>0.568</td>
<td>0.568</td>
<td>56.2</td>
<td>0.043</td>
<td>0.0</td>
</tr>
<tr>
<td>Winter</td>
<td>06:00</td>
<td>0.091</td>
<td>0.248</td>
<td>7.3</td>
<td>0.002</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>14:00</td>
<td>0.155</td>
<td>0.327</td>
<td>13.2</td>
<td>0.006</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>17:00</td>
<td>0.071</td>
<td>0.116</td>
<td>1.8</td>
<td>0.000</td>
<td>0.0</td>
</tr>
<tr>
<td>Spring/Fall</td>
<td>08:00</td>
<td>0.165</td>
<td>0.674</td>
<td>51.7</td>
<td>0.047</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>14:00</td>
<td>0.521</td>
<td>0.944</td>
<td>114.8</td>
<td>0.147</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>17:00</td>
<td>0.169</td>
<td>0.335</td>
<td>14.1</td>
<td>0.006</td>
<td>0.0</td>
</tr>
<tr>
<td>Annual average</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.0</td>
</tr>
</tbody>
</table>

7.2.3 Synthesized Solutions

The evolutionary algorithm was set up to synthesise configurations for the low-load building system. The default settings for the EA (see Chapter 5, Table 5.3) were used. 25 separate trial optimizations were performed to test the consistency of the approach. Table 7-6 summarises the results from the 25 runs.

Feasible solutions were found in all trial optimizations within 10,000 generations. The mean of the objective function values, 0.213kW, is higher than 0.091kW for the benchmark system (Table 7-6). However, 28% of the solutions have an objective function that is lower than the objective function value of the benchmark system. The objective function value of these solutions is also significantly lower than that of the remaining trial solutions, with a mean of 65.5W in comparison to 270.4W. This is an indication of the multi-modal nature of the optimization problem and that the search is able to find optimum solutions for this class of problem. However, several trial optimizations are required to ensure that a (near) optimum solution is found.

The effectiveness of the search is further indicated by the rate of convergence on to feasible solutions. The search was able to find a feasible solution with a mean of 230 generations. Finally, the mean number of topologies searched during the optimization (7.3x10^5) is small in comparison to the total size of the topological search space of 5.8x10^27. This again, is indicative of the effectiveness of the optimization algorithm.
### Table 7-6 Summary of synthesised solutions from 25 separate trial optimisations

<table>
<thead>
<tr>
<th>Trial number (Rank)</th>
<th>Objective Function</th>
<th>First feasible solution found in generation</th>
<th>Total number of generations</th>
<th>Total number of topologies searched</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 (1) 0.061</td>
<td>163</td>
<td>5,705</td>
<td>832,584</td>
<td></td>
</tr>
<tr>
<td>1 (2) 0.063</td>
<td>202</td>
<td>6,580</td>
<td>806,553</td>
<td></td>
</tr>
<tr>
<td>22 (3) 0.063</td>
<td>144</td>
<td>7,596</td>
<td>925,824</td>
<td></td>
</tr>
<tr>
<td>24 (4) 0.064</td>
<td>175</td>
<td>5,749</td>
<td>906,736</td>
<td></td>
</tr>
<tr>
<td>10 (5) 0.068</td>
<td>237</td>
<td>8,028</td>
<td>719,304</td>
<td></td>
</tr>
<tr>
<td>2 (6) 0.069</td>
<td>211</td>
<td>7,228</td>
<td>792,694</td>
<td></td>
</tr>
<tr>
<td>9 (7) 0.071</td>
<td>202</td>
<td>6,538</td>
<td>828,420</td>
<td></td>
</tr>
<tr>
<td><strong>Benchmark</strong> 0.091</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>18 (8) 0.187</td>
<td>307</td>
<td>9,496</td>
<td>858,718</td>
<td></td>
</tr>
<tr>
<td>3 (9) 0.193</td>
<td>149</td>
<td>9,165</td>
<td>867,484</td>
<td></td>
</tr>
<tr>
<td>15 (10) 0.194</td>
<td>293</td>
<td>10,000</td>
<td>585,559</td>
<td></td>
</tr>
<tr>
<td>7 (11) 0.218</td>
<td>267</td>
<td>8,679</td>
<td>684,004</td>
<td></td>
</tr>
<tr>
<td>14 (12) 0.218</td>
<td>189</td>
<td>9,000</td>
<td>675,809</td>
<td></td>
</tr>
<tr>
<td>20 (13) 0.221</td>
<td>458</td>
<td>7,000</td>
<td>785,991</td>
<td></td>
</tr>
<tr>
<td>21 (14) 0.230</td>
<td>266</td>
<td>10,000</td>
<td>632,983</td>
<td></td>
</tr>
<tr>
<td>6 (15) 0.251</td>
<td>215</td>
<td>8,802</td>
<td>680,306</td>
<td></td>
</tr>
<tr>
<td>4 (16) 0.261</td>
<td>319</td>
<td>5,606</td>
<td>828,979</td>
<td></td>
</tr>
<tr>
<td>13 (17) 0.273</td>
<td>228</td>
<td>7,912</td>
<td>693,946</td>
<td></td>
</tr>
<tr>
<td>12 (18) 0.306</td>
<td>277</td>
<td>8,606</td>
<td>743,398</td>
<td></td>
</tr>
<tr>
<td>11 (19) 0.307</td>
<td>163</td>
<td>7,352</td>
<td>795,471</td>
<td></td>
</tr>
<tr>
<td>25 (20) 0.307</td>
<td>190</td>
<td>7,848</td>
<td>738,032</td>
<td></td>
</tr>
<tr>
<td>17 (21) 0.315</td>
<td>193</td>
<td>9,196</td>
<td>656,282</td>
<td></td>
</tr>
<tr>
<td>5 (22) 0.323</td>
<td>220</td>
<td>10,000</td>
<td>593,406</td>
<td></td>
</tr>
<tr>
<td>16 (23) 0.324</td>
<td>190</td>
<td>7,033</td>
<td>700,123</td>
<td></td>
</tr>
<tr>
<td>19 (24) 0.332</td>
<td>241</td>
<td>8,342</td>
<td>683,079</td>
<td></td>
</tr>
<tr>
<td>23 (25) 0.407</td>
<td>252</td>
<td>10,000</td>
<td>815,179</td>
<td></td>
</tr>
<tr>
<td><strong>Average</strong> 0.213</td>
<td>230</td>
<td>8058</td>
<td>7.30E+06</td>
<td></td>
</tr>
</tbody>
</table>

For the low-load building system, it was expected that the zone conditions could be maintained through free cooling alone. The optimality of the system is dependent on the minimization of the fan capacity. In this respect, the benchmark systems are at a disadvantage, since they were designed to operate with full mechanical air conditioning, and not to minimize the fan capacity. The fan capacity of the best of the synthesized systems (Figure 7-3) is lower than that of the benchmark system at all load conditions (see Table 7-7). This is due to the optimization placing the air-handling components in air paths that at all load conditions, have very low or zero air flow rates. Also, the components are shaded grey due to not being operated at any load condition. It can be concluded that the system in Figure 7-3 is (near) optimum for the given design requirements, as the fan capacity is minimized through the placement of the air-handling components in low air flow rate ducts, and the system is able to meet all load conditions without mechanical air conditioning.
The EA approach developed in this research has been proved capable of synthesising (near) optimum configurations for a low load building system. In 25 separate optimisation trials, the algorithm managed to find feasible configurations in an average of 230 generations, which is equivalent to about 230,000 solution evaluations. The estimated energy
consumption of the best configuration found in the 25 trials is 33% lower than that for the 2-zone single-duct benchmark system. This was achieved by identifying the redundant air-handling components in the system, and moving them to the airflow branches in which the flow rate was low or zero.

Comparing to the basic single-zone problem, however, the 2-zone configuration to be synthesised in this example is more complex in terms of both topology, and operations. Unlike the single-zone example, in which the global optimum solution was invariably found in all 4 trials with more than 500 generations, only 7 of the 25 trials on the 2-zone problem found a solution better than the benchmark. This suggests that multiple trial optimizations are required to find a (near) optimum solution for a complex problem.

### 7.3 Summary

Two tests have been carried out to validate the approach. The first test is for the generation of HVAC configuration with minimum set of components and a single design condition to satisfy. The optimisation result was compared to that from an exhaustive search. It proved that the optimisation approach was able find the optimum solution in this case. It also showed, comparing to the exhaustive search, much fewer evaluations are required by the optimisation to find the optimum solution.

The second test is to generate a 2-zone configuration. Although the complexity of the configuration, in terms of components and topology, is in the same scale as those to be generated in the experiments in the next chapter, the operations of the configuration are considered easier to solve. The design target was for a low-load building situated in a temperate climate, where free cooling is available throughout the year. 25 separate runs were carried out. Feasible solutions have been found in all runs, among which there are 7 generated configurations that outperformed the 2-zone single-duct benchmark system. Analysing the generated configurations showed that the optimisation algorithm was able to exploit the potential of free cooling, as well as minimise fan energy consumption by moving redundant components out of the main circulation loop.
The Evolutionary Algorithm-based approach to HVAC system configuration synthesis has been validated with two example optimisations described in the previous chapter. The two example problems, however, are considered "easy" because they are either simple in terms of topology (for having a small set of components), or simple in terms of system operation (as no mechanical conditioning were required). A harder task has been laid out in this chapter, in order to test the effectiveness of the approach in tackling more complex design problems.

In this chapter, the example design problem is first explained. The task for the EA approach is to synthesise HVAC system configuration for a high-load building where mechanical air-conditioning is required. The performance of a number of conventional system configurations is studied, hence providing benchmarks to the generated configurations. The performance and behaviour of EA is investigated with a number of trial optimisations. The objective is to evaluate, (1) the consistency of the configuration synthesis approach; (2) the optimality of the synthesised configurations; and (3) the behaviour of the optimisation algorithm in topological search.
8.1 Experiment setup

A "high load" building is set up as the test problem for the experiment. The test problem has been carefully designed to achieve the objectives of the experiment – to reveal the capability and characteristics of the optimisation algorithm.

8.1.1 Objectives

The capability of the optimisation procedure is often defined as the robustness of the approach, which includes the optimality of the solutions found for a range of example problems, and the consistency of the solutions found for different initial search conditions.

In this research, the optimality of the solutions is determined in two ways: firstly, by comparing the synthesized systems energy use to the minimum system energy use, as determined from a thermodynamic analysis of the building loads and boundary conditions; and secondly, by comparing the synthesized systems energy use to that of six benchmark systems, 5 typical HVAC system configurations, and 1 conceptually optimal configuration (Chapter 3, section 3.2.4).

The solutions found by all optimization methods are subject to the initial conditions of the search (such as the initial estimate of the solution). Since Evolutionary Algorithms (EA) use probabilistic search operators they may be prone to a higher variability in the optimality of the solutions than methods that employ deterministic strategies. Multiple separate trials have been performed for the experiment. Each trial is initialized with a different random population. The results from the trials will be summarised to provide statistics of consistency.

Analysis of the behaviour of the search approach is also part of the experimental objectives. The characteristics of topological exploration with the present approach will be discussed.

8.1.2 Test Problem

Building and design conditions

The building used in this study is based on two mid-level zones in a multi-story building. One façade (and zone) is orientated to face east and the other the west. Both zones have high
level of glazing; therefore solar gain is a significant factor. The zones are also densely occupied with people and equipments, which result in high internal gain and fresh air demand. Thermal loads of the zones have been derived for Oklahoma City, OK, USA. The building requires full mechanical air conditioning in order to maintain the zone conditions.

Table 8-1 gives the ambient conditions and load weights for the "high load" building. In this research, 9 operation conditions are chosen arbitrarily, which, however, cover the coldest day in winter and the warmest day in summer. The "weights" in the third column represent the duration of occurrences of similar weather conditions in a typical year. These will be used in calculation of the annual average energy consumption (see Chapter 4, section 4.2.2). All conditions are arbitrarily assigned same weight of 0.1, except for the mid-day in spring or fall, which has a weight of 0.2.

Table 8-1 Ambient design conditions for the high load building

<table>
<thead>
<tr>
<th>Data Point</th>
<th>Ambient Condition (Oklahoma City, OK, USA)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time of year</td>
</tr>
<tr>
<td>Summer</td>
<td>08:00</td>
</tr>
<tr>
<td></td>
<td>14:00</td>
</tr>
<tr>
<td></td>
<td>17:00</td>
</tr>
<tr>
<td>Winter</td>
<td>08:00</td>
</tr>
<tr>
<td></td>
<td>14:00</td>
</tr>
<tr>
<td></td>
<td>17:00</td>
</tr>
<tr>
<td>Spring/Fall</td>
<td>08:00</td>
</tr>
<tr>
<td></td>
<td>14:00</td>
</tr>
<tr>
<td></td>
<td>17:00</td>
</tr>
</tbody>
</table>

Table 8-2 and Table 8-3 give the corresponding zone design conditions and loads for the east and west zones. The zone loads are calculated with consideration of heat transfer, solar gain, and internal gains. The latent loads and fresh air requirements are determined by human occupancy; and have been fixed across all load conditions. It is assumed that the east zone accommodates 6 persons, while the west zone accommodates 2. Therefore the latent gain and fresh air demand for the east zone are 600W and 0.096kg/s, in contrast to 200W and 0.032kg/s for the west zone. The zone sensible loads, however, vary significantly between load conditions. The sensible heat gains are driven primarily by the fabric heat transfer, in particular the solar gain (note the change of load between morning and afternoon). The east and west zone can have different temperature settings at the same time. Temperature (or enthalpy) difference enables opportunities for saving energy with inter-zone airflow. As the set points for relative humidity of each zone are fixed to 50%, the actual humidity
ratio settings change with the zone temperature. From a comparison of the design temperatures and humidity ratios in each zone (Table 8-2 and Table 8-3), it is evident that at some load conditions, the capacity of the HVAC system can be reduced by transferring energy between the two zones through inter-zone airflow.

### Table 8-2 Design conditions of the east zone in the high load building

<table>
<thead>
<tr>
<th>Data Point</th>
<th>Design condition</th>
<th>Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time of year</td>
<td>Time of day</td>
<td>Dry bulb temp. (°C)</td>
</tr>
<tr>
<td>Summer</td>
<td>08:00</td>
<td>20.0</td>
</tr>
<tr>
<td></td>
<td>14:00</td>
<td>24.0</td>
</tr>
<tr>
<td></td>
<td>17:00</td>
<td>22.0</td>
</tr>
<tr>
<td>Winter</td>
<td>08:00</td>
<td>22.0</td>
</tr>
<tr>
<td></td>
<td>14:00</td>
<td>22.0</td>
</tr>
<tr>
<td></td>
<td>17:00</td>
<td>22.0</td>
</tr>
</tbody>
</table>

### Table 8-3 Design conditions of the west zone in the high load building

<table>
<thead>
<tr>
<th>Data Point</th>
<th>Design condition</th>
<th>Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time of year</td>
<td>Time of day</td>
<td>Dry bulb temp. (°C)</td>
</tr>
<tr>
<td>Summer</td>
<td>08:00</td>
<td>22.0</td>
</tr>
<tr>
<td></td>
<td>14:00</td>
<td>20.0</td>
</tr>
<tr>
<td></td>
<td>17:00</td>
<td>20.0</td>
</tr>
<tr>
<td>Winter</td>
<td>08:00</td>
<td>18.0</td>
</tr>
<tr>
<td></td>
<td>14:00</td>
<td>20.0</td>
</tr>
<tr>
<td></td>
<td>17:00</td>
<td>20.0</td>
</tr>
<tr>
<td>Spring/Fall</td>
<td>08:00</td>
<td>22.0</td>
</tr>
<tr>
<td></td>
<td>14:00</td>
<td>22.0</td>
</tr>
<tr>
<td></td>
<td>17:00</td>
<td>22.0</td>
</tr>
</tbody>
</table>

This test problem is specified such that under some load conditions, the energy consumption of the system can only be minimized if air is circulated from one zone to another. Therefore, this test problem is used to examine not only the ability of the optimization to simultaneously optimize the system topology, the air flow rates and HVAC component capacities, but also the ability of the search to synthesize topologies that minimize energy use through the circulation of air between zones.
Chapter 8 Example optimisation: two-zone system

Calculation of expected capacity

In each case, the "annual" performance has been modelled by integrating the capacity of the HVAC components over nine load conditions. The nine load conditions are nominally, early morning, afternoon, and an early evening for each of three seasons, winter, spring/fall, and summer. An energy balance analysis (see Chapter 3, Figure 3-7 for example) has been used to identify the minimum system energy use the building. The required mechanical thermal input, notionally the target capacity, is calculated for each of the 9 design conditions (see Table 8-4). The system target capacity for the building shows that both zones require full mechanical air conditioning during the winter and summer seasons, although during the intermediate seasons, the load conditions can be met through free cooling.

Table 8-4 System target capacities of the high load building

<table>
<thead>
<tr>
<th>Data Points</th>
<th>Time of year</th>
<th>Total zone load (kW)</th>
<th>Minimal outside air load (kW)</th>
<th>Exhaust from</th>
<th>Expected Capacity (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>08:00</td>
<td>7.375</td>
<td>3.098</td>
<td>West</td>
<td>-10.472</td>
</tr>
<tr>
<td>Summer</td>
<td>14:00</td>
<td>8.039</td>
<td>4.070</td>
<td>East</td>
<td>-12.119</td>
</tr>
<tr>
<td></td>
<td>17:00</td>
<td>8.231</td>
<td>4.416</td>
<td>East</td>
<td>-12.677</td>
</tr>
<tr>
<td>Winter</td>
<td>08:00</td>
<td>-0.609</td>
<td>-6.182</td>
<td>West</td>
<td>6.781</td>
</tr>
<tr>
<td></td>
<td>14:00</td>
<td>3.054</td>
<td>-6.093</td>
<td>West</td>
<td>3.039</td>
</tr>
<tr>
<td></td>
<td>17:00</td>
<td>0.999</td>
<td>-6.234</td>
<td>West</td>
<td>6.334</td>
</tr>
<tr>
<td>Spring/Fall</td>
<td>08:00</td>
<td>3.079</td>
<td>-2.522</td>
<td>East/West</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>14:00</td>
<td>5.480</td>
<td>-1.050</td>
<td>East/West</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>17:00</td>
<td>3.365</td>
<td>-1.287</td>
<td>East/West</td>
<td>0.0</td>
</tr>
<tr>
<td>Annual average</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-5.942</td>
</tr>
</tbody>
</table>

It is worth noting that the target capacity is calculated under idealistic assumptions, without concern of practicality. It is assumed that, firstly, the sensible gains and the latent gains are not discriminated; and secondly, the gains in two zones can always offset each other if they have opposite signs. For example, in winter condition at 8:00, the sum of sensible and latent gains in the east zone is 1.214kW, whereas the total gain in the west zone is -1.823kW; as a result, the total gain in the system is -0.609kW.

Table 8-4 also indicates the optimal choice of the exhaust air condition in order to minimise fresh air load. The air from the east zone must be exhausted through the west zone during winter operation and in one condition of summer operation (Figure 8-1b); and that this flow configuration is reversed during the other two conditions of summer operation (Figure 8-1a). During Spring/Fall operation, the air flow is exhausted directly from each zone (Figure 8-1c). Again there is no discrimination between sensible load and latent load.
Exhaust air condition is chosen on minimum enthalpy difference between the exhaust air and the outside air, unless free cooling is preferred.

![Diagram of exhaust airflow arrangement](image)

Figure 8-1 Exhaust airflow arrangement

Unlike the configuration models, the calculation of the target capacity described above does not include the capacity of fans that are potentially required to circulate the air. This can be considered as another idealistic assumption that the preferred air condition can be achieved without mechanical ventilation.

**Tolerance and system efficiency**

Due to the presence of the idealistic assumptions, it is expected that none of the configurations in either conventional or innovative categories can achieve the target capacity. The energy consumption of a configuration should be always larger than the target capacity. Therefore a factor such as \( \frac{\text{target capacity}}{\text{energy consumption}} \times 100\% \) is a good measure of how close the configuration performs comparing to the ideal case.

The presence of tolerance on the supply air conditions in the optimization, however, may cause the optimal system capacity to be lower than the target capacity, which is calculated for no tolerance on the zone conditions. The impact of the tolerance on the system capacity is dependent on the supply air flow rate, as well as the errors in supply air temperature and humidity ratio:

\[
Q_{\text{tolerance}} = \dot{M}_s \cdot (C_p \cdot \delta T_{\text{sup}} + L \cdot \delta \varphi_{\text{sup}})
\]  

(8-1)

Where:

- \( Q_{\text{tolerance}} \) — The capacity error caused by tolerated supply air condition error [kW]
\[ \dot{M}_a \] — Supply air mass flow rate [kg/s]

\[ \delta T_{\text{sup}} \] — Absolute error in supply air temperature [°C]

\[ \delta W_{\text{sup}} \] — Absolute error in supply air humidity ratio [kg/kg]

For example, given the present tolerance setting of 0.2°C on supply temperature and 0.00075 kg moisture/kg dry air on the humidity ratio at supply air flow rate of 1.0 kg/s, the maximal error on capacity is 1.0 kg/s \((0.2°C \times 1.004 \text{kJ/kg°C} + 0.00075 \text{kg/kg} \times 2454 \text{kJ/kg}) = 2.041 \text{kW}\). Comparing to the target capacities in the Table 8-4, the potential error caused by the tolerance is significant. The impact of tolerance will be further analysed in the discussion of the experimental results.

With the presence of tolerance, a “Configuration Efficiency” is defined as the following equation:

\[
Eff = \frac{Q_{\text{target}}}{Q_{\text{total}} + Q_{\text{tolerance}}} \times 100\%
\] (8-2)

Where:

\[ Q_{\text{target}} \] — The target capacity of heating, cooling, and humidification

\[ Q_{\text{total}} \] — The total capacity of the components in the system, excluding fans

\[ Q_{\text{tolerance}} \] — The error in capacity caused by the presence of tolerance

### 8.2 Benchmark Systems Performance

Six configurations are used as benchmark systems, to which the performance of the synthesised configurations is compared. Five of the six configurations are conventional designs; and the last benchmark configuration is the conceptual “optimum” configuration derived from the analysis of configurations (see Chapter 3, section 3.2.4). The 5 conventional configurations are: (1) a single-duct system with reheat terminals; (2) a dual-duct system; and (3) 3 fan-coil systems with different exhaust arrangement. The “optimum” configuration is also fan-coil-based, but with inter-zone recirculation path.

The operation of all benchmark systems has been optimized, so that system performance is not biased by the operating strategy. The optimum control strategy minimizes the system
energy use at each load condition by optimizing the air flow rates in each part of the system, together with the capacity of the components.

### 8.2.1 Single-Duct Benchmark Configuration

Figure 8-2 gives a schematic diagram of the single-duct benchmark configuration. In order to provide sufficient humidity control, steam injectors had to be added in the reheat terminals. The components shaded grey were not operated at any load condition (and are therefore redundant).

![Figure 8-2 Single-duct system configuration](image)

The optimum performance of the single-duct system is given in Table 8-5. It is clear to see, in the summer conditions at 14:00 and 17:00, over cooling and reheating were required to control humidity. This was caused by the excess outside air being taken into the system (the minimum fresh air required is 0.128kg/s). Excess outside air intake meant excess moisture to remove, therefore overcooling and reheating were the only solution given the present set of components. The requirement of the excess fresh air was caused by the configuration design and the zone load conditions.

As has been discussed in Chapter 3, section 3.3.2, the condition that the total outside air flow rate is higher than the minimum required to maintain the indoor air quality of both zones, can be explained by the centralized cooling and re-circulation of the extract air (as opposed to separate re-circulation and cooling for each zone). When the extract air is re-
circulated and mixed centrally, the outside air flow rate to each zone is in proportion to the supply air flow rate to each zone. If the ratio of the supply air flow rate to each zone is different to the ratio of the outside air flow rates required to maintain the indoor air quality of the zones, then it may be necessary to increase the outside air flow rate entering the system. For the example of the summer operation at 14:00, Figure 8-3 illustrates the sensible loads, the optimized air flow rates, and air temperatures in the benchmark system.

### Table 8-5 Optimum performance of the single-duct benchmark system

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Total Fresh Air (kg/s)</th>
<th>Total Circulated Air (kg/s)</th>
<th>Total Pressure Loss (Pa)</th>
<th>Total Circulation Consump. (kW)</th>
<th>Total Heating Duty (kW)</th>
<th>Total Cooling Duty (kW)</th>
<th>Total Humid. Duty (kW)</th>
<th>Total Energy Consum. (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>08:00</td>
<td>0.128</td>
<td>1.437</td>
<td>253</td>
<td>0.492</td>
<td>0</td>
<td>-9.851</td>
<td>0.934</td>
</tr>
<tr>
<td></td>
<td>14:00</td>
<td>0.243</td>
<td>1.158</td>
<td>219</td>
<td>0.344</td>
<td>5.667</td>
<td>-22.398</td>
<td>0.129</td>
</tr>
<tr>
<td></td>
<td>17:00</td>
<td>0.298</td>
<td>1.135</td>
<td>184</td>
<td>0.284</td>
<td>1.382</td>
<td>-18.818</td>
<td>20.464</td>
</tr>
<tr>
<td>Winter</td>
<td>08:00</td>
<td>0.128</td>
<td>1.121</td>
<td>145</td>
<td>0.220</td>
<td>5.772</td>
<td>0</td>
<td>0.592</td>
</tr>
<tr>
<td></td>
<td>14:00</td>
<td>0.188</td>
<td>0.910</td>
<td>98</td>
<td>0.121</td>
<td>3.857</td>
<td>0</td>
<td>0.704</td>
</tr>
<tr>
<td></td>
<td>17:00</td>
<td>0.128</td>
<td>1.142</td>
<td>149</td>
<td>0.230</td>
<td>4.104</td>
<td>0</td>
<td>4.334</td>
</tr>
<tr>
<td>Spring/Fall</td>
<td>08:00</td>
<td>0.193</td>
<td>0.484</td>
<td>28</td>
<td>0.016</td>
<td>0.267</td>
<td>0</td>
<td>0.283</td>
</tr>
<tr>
<td></td>
<td>14:00</td>
<td>0.838</td>
<td>1.093</td>
<td>174</td>
<td>0.258</td>
<td>0</td>
<td>0</td>
<td>0.258</td>
</tr>
<tr>
<td></td>
<td>17:00</td>
<td>0.383</td>
<td>0.524</td>
<td>39</td>
<td>0.028</td>
<td>0</td>
<td>0</td>
<td>0.028</td>
</tr>
</tbody>
</table>

In Figure 8-3, \( m \) is the air flow rate, with superscripts \( O \), indicating outside air, \( M \) the mixed air, and \( S \) supply air flow rate; subscripts \( E \) and \( W \) indicate the East and West zones.

In order to simplify the discussion, only sensible loads is considered in this analysis (although the optimization was performed with the latent loads). Figure 8-3 indicates that the west zone has the highest sensible gain and therefore it is expected that the west zone dominates the cooling coil operation. This is reflected in the optimization result as the air supplied to the west zone is at a lower temperature than to the east zone. The west zone supply air temperature is 7°C lower than the zone temperature. This is the limiting temperature difference, the room-to-supply air temperature difference being constrained to prevent cold dense air from “dumping” from the supply diffusers. The optimization found a solution on this constraint bound as maximizing the room-to-supply air temperature difference will minimize the required supply air flow rate (and hence fan capacity). The 0.71 kg/s airflow rate to the west zone can therefore be considered to be the optimum flow rate for the configuration.
Figure 8-3 Optimum operation of the single-duct system, summer at 14:00

Given an airflow rate of 0.71 kg/s to the west zone, the airflow rate to the east zone can be calculated, so that the minimum outside airflow is supplied. The minimum outside airflow rates required to maintain indoor air quality are 0.096 kg/s to the east zone and 0.032 kg/s to the west zone, giving a total of 0.128 kg/s of outside air. Given the outside airflow rate to the West zone ($\dot{m}_w^O$), the total outside airflow rate into the system ($\dot{m}^O$), and the supply airflow rate to the zone ($\dot{m}_w^S$), the mixed airflow rate ($\dot{m}^M$), is given by:

$$\dot{m}^M = \frac{\dot{m}_w^S}{\dot{m}^O} \dot{m}^O$$

(8-3)

That is, the outside airflow rate to the zone is in proportion to the ratio of zone supply airflow rate to the total (mixed) air flow rate in the system:

$$\dot{m}_w^O = \frac{\dot{m}_w^S}{\dot{m}^M} \dot{m}^O$$

(8-4)

$$\dot{m}_E^O = \frac{\dot{m}_E^S}{\dot{m}^M} \dot{m}^O$$

(8-5)

Given an outside airflow rate to the west zone of $\dot{m}_w^O = 0.032$ kg/s, and a total outside airflow rate entering the system of $\dot{m}^O = 0.128$ kg/s, Equation 7-1 gives a mixed airflow rate of $\dot{m}^M = 2.86$ kg/s. Given an airflow rate to the west zone of 0.71 kg/s and a mixed airflow rate of 2.86 kg/s, the east zone supply airflow rate is 2.14 kg/s. With a 2.2 kw gain to the
east, this air flow rate results in a supply air temperature of 23°C. Given that this is ~13°C higher than the mixed air temperature (which is required to maintain the west zone conditions), a supply air low rate of 2.14kg/s to the east zone would not only result in a high fan capacity, but also a high re-heat capacity.

The supply air flow rate to the east zone can be reduced if the outside air flow rate entering the system (\(m^O\)), is increased (from Equation 7.2). This would increase the outside air load, but reduce the east zone supply air flow rate required to maintain zone outside air flow rate, and hence reduce the zone re-heat and fan capacities. This is the case shown in Figure 8-3, where the optimization has minimized the system energy use by a trade-off between the outside airflow rate and the re-heat and fan capacities. Although the system operation is optimized, the high outside airflow rate results in low system efficiency. Table 8-6 summarises the efficiency of the system (Equation 7-1) in each condition.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Target capacity (kW)</th>
<th>Total capacity (kW)</th>
<th>Tolerated error (kW)</th>
<th>Capacity overhead (kW)</th>
<th>Config. Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>08:00 10.472</td>
<td>8.851</td>
<td>2.458</td>
<td>0.835</td>
<td>92.6%</td>
</tr>
<tr>
<td></td>
<td>14:00 12.110</td>
<td>28.196</td>
<td>2.352</td>
<td>18.448</td>
<td>39.8%</td>
</tr>
<tr>
<td></td>
<td>17:00 12.877</td>
<td>20.180</td>
<td>1.983</td>
<td>9.468</td>
<td>57.3%</td>
</tr>
<tr>
<td>Winter</td>
<td>08:00 8.791</td>
<td>5.772</td>
<td>1.709</td>
<td>0.690</td>
<td>90.8%</td>
</tr>
<tr>
<td></td>
<td>14:00 3.039</td>
<td>4.580</td>
<td>1.858</td>
<td>3.377</td>
<td>47.4%</td>
</tr>
<tr>
<td></td>
<td>17:00 5.334</td>
<td>4.104</td>
<td>1.911</td>
<td>0.680</td>
<td>88.7%</td>
</tr>
<tr>
<td>Spring</td>
<td>08:00 0</td>
<td>0.287</td>
<td>0.500</td>
<td>0.287</td>
<td>100.0%</td>
</tr>
<tr>
<td></td>
<td>14:00 0</td>
<td>0</td>
<td>1.797</td>
<td>0</td>
<td>100.0%</td>
</tr>
<tr>
<td></td>
<td>17:00 0</td>
<td>0</td>
<td>0.722</td>
<td>0</td>
<td>100.0%</td>
</tr>
<tr>
<td>Annual average</td>
<td>5.642</td>
<td>7.193</td>
<td>1.703</td>
<td>3.375</td>
<td>81.8%</td>
</tr>
</tbody>
</table>

The summer operation of the single-duct system has the lowest efficiency, particularly at 14:00 and 17:00. As discussed above, this is mainly owing to the excess outside air intake and the simultaneous cooling, dehumidification and zonal reheating. Even in the operation condition at summer 8:00, winter 8:00, and winter 17:00, where fresh air supply has been minimized, the efficiency is lower than some of the other benchmark systems. This can be explained in the following reasons. First, in the single-duct configuration, all the components locate in the supply path; therefore impose most restriction to air flow. As a result, the optimisation tends to trade off coil capacities to lower air flow rate. Comparing the values of “Total circulated air” and “Total circulation consumption” in Table 8-5 and those in Table...
8-9, it is easy to notice that although the air flow rates are generally lower for the single-duct configuration, the fan capacities are higher than those for the fan-coil-based configuration.

Secondly, the single-duct configuration is unable to minimise the outside air load, despite minimising the fresh air intake. As in Table 8-4, the target capacity calculation indicates a need to exhaust the east zone air through the west zone for the three conditions. This is unachievable for the configuration. It is worthwhile to mention that for the winter condition at 14:00, all the benchmark systems perform “poorly” regarding the configuration efficiency scores. This will be explained later in 8.2.4.

During spring and fall, the system operates with an efficiency of 100% for all load conditions, as the system is able to operate with free-cooling. The only exception was that at 08:00 when the east zone requires 0.27 kW of heating. This comes from the assumption in calculating the target capacity – the sensible and latent loads are interchangeable. The conversion of sensible and latent form is not achievable, however, with the present set of components. Therefore in the condition at 8:00 during the swing season, the target sensible load is - 0.247 kW, and the latent load is 0.80 kW. This explains the requirement of 0.27 kW heating, which occurs in all benchmark configurations. However, as it is a “small” number, the configurations are still considered 100% efficient in this design condition.

8.2.2 Dual-Duct Benchmark Configuration

Figure 8-4 gives a schematic diagram of the dual-duct benchmark system. Steam injectors have been added in the dual-duct terminals, so that zonal humidity can be controlled. The west zone humidifier shaded gray was not operated at any load condition. The optimum performance of the dual-duct system is given in Table 8-7. By mixing air from the “hot” duct and the “cold” duct, the system avoided simultaneously cooling and reheating, therefore significantly reduced capacity in summer conditions. This is the advantage of the dual-duct system comparing to the single-duct configuration.
Figure 8-4 Dual-duct system configuration

Table 8-7 Optimum performance of the dual-duct benchmark system

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Total Fresh Air (kg/s)</th>
<th>Total Circulated Air (kg/s)</th>
<th>Total Pressure Loss (Pa)</th>
<th>Total Circulation Consump. (kW)</th>
<th>Total Heating Duty (kW)</th>
<th>Total Cooling Duty (kW)</th>
<th>Total Humid. Duty (kW)</th>
<th>Total Energy Consum. (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>08:00</td>
<td>0.128</td>
<td>1.299</td>
<td>252</td>
<td>0.444</td>
<td>0</td>
<td>-9.062</td>
<td>0</td>
<td>9.506</td>
</tr>
<tr>
<td>14:00</td>
<td>0.166</td>
<td>1.661</td>
<td>417</td>
<td>0.939</td>
<td>0</td>
<td>-12.075</td>
<td>0</td>
<td>13.006</td>
</tr>
<tr>
<td>17:00</td>
<td>0.185</td>
<td>1.594</td>
<td>382</td>
<td>0.825</td>
<td>0</td>
<td>-11.849</td>
<td>0</td>
<td>12.675</td>
</tr>
<tr>
<td>Winter</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>08:00</td>
<td>0.129</td>
<td>1.085</td>
<td>179</td>
<td>0.263</td>
<td>5.825</td>
<td>0</td>
<td>0</td>
<td>6.088</td>
</tr>
<tr>
<td>14:00</td>
<td>0.189</td>
<td>0.995</td>
<td>147</td>
<td>0.198</td>
<td>3.892</td>
<td>0</td>
<td>0.678</td>
<td>4.769</td>
</tr>
<tr>
<td>17:00</td>
<td>0.128</td>
<td>1.090</td>
<td>178</td>
<td>0.263</td>
<td>4.093</td>
<td>0</td>
<td>0.049</td>
<td>4.405</td>
</tr>
<tr>
<td>Spring/Fall</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>08:00</td>
<td>0.193</td>
<td>0.455</td>
<td>31</td>
<td>0.019</td>
<td>0.267</td>
<td>0</td>
<td>0</td>
<td>0.286</td>
</tr>
<tr>
<td>14:00</td>
<td>0.838</td>
<td>1.093</td>
<td>182</td>
<td>0.270</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.270</td>
</tr>
<tr>
<td>17:00</td>
<td>0.383</td>
<td>0.524</td>
<td>42</td>
<td>0.030</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.030</td>
</tr>
<tr>
<td>Annual average</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.130</td>
</tr>
</tbody>
</table>

Figure 8-5 shows the system operation at 14:00 in summer. As for the single-duct system (Figure 8-3), two design constraints are active for this load condition. The supply air temperature to the higher load west zone is 7°C lower than the zone temperature (this being the maximum room-to-supply air temperature difference), and the outside air flow rate to east zone is on the lower limit for indoor air quality (0.096 kg/s). Note that the outside air flow rate to the west zone is higher than the minimum requirement (0.032 kg/s), which is evidently, determined by the trade-off between fan capacity and the outside air load.
Unlike the single-duct system, the supply air condition to the west zone is achieved without the need for re-heat by mixing air from the “hot” and “cold” ducts. Since no re-heating is used, the air in the hot duct is at the same temperature as the air leaving the primary cooling coil, which is also the condition of the air supplied to the lower load east zone.

Figure 8-5 Optimum operation of the dual-duct system, summer at 14:00

Table 8-8 Summary of system efficiency of the dual-duct benchmark system

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Target capacity</th>
<th>Total capacity</th>
<th>Tolerated error</th>
<th>Capacity overhead</th>
<th>Config. Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(kW)</td>
<td>(kW)</td>
<td>(kW)</td>
<td>(kW)</td>
<td>(%)</td>
</tr>
<tr>
<td>Summer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>08:00</td>
<td>10.472</td>
<td>9.062</td>
<td>2.234</td>
<td>0.824</td>
<td>92.7%</td>
</tr>
<tr>
<td>14:00</td>
<td>12.110</td>
<td>12.067</td>
<td>1.882</td>
<td>1.840</td>
<td>86.8%</td>
</tr>
<tr>
<td>17:00</td>
<td>12.677</td>
<td>11.849</td>
<td>3.106</td>
<td>2.278</td>
<td>84.8%</td>
</tr>
<tr>
<td>Winter</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>08:00</td>
<td>6.791</td>
<td>5.825</td>
<td>1.669</td>
<td>0.703</td>
<td>90.6%</td>
</tr>
<tr>
<td>14:00</td>
<td>3.039</td>
<td>4.570</td>
<td>1.915</td>
<td>3.446</td>
<td>46.9%</td>
</tr>
<tr>
<td>17:00</td>
<td>5.334</td>
<td>4.142</td>
<td>1.828</td>
<td>0.635</td>
<td>89.4%</td>
</tr>
<tr>
<td>Spring/Fall</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>08:00</td>
<td>0</td>
<td>0.267</td>
<td>0.499</td>
<td>0.267</td>
<td>100.0%</td>
</tr>
<tr>
<td>14:00</td>
<td>0</td>
<td>0</td>
<td>1.797</td>
<td>0</td>
<td>100.0%</td>
</tr>
<tr>
<td>17:00</td>
<td>0</td>
<td>0</td>
<td>0.722</td>
<td>0</td>
<td>100.0%</td>
</tr>
<tr>
<td>Annual average</td>
<td><strong>5.042</strong></td>
<td><strong>4.778</strong></td>
<td><strong>1.745</strong></td>
<td><strong>0.999</strong></td>
<td><strong>89.1%</strong></td>
</tr>
</tbody>
</table>

The elimination of zonal re-heat and a lower outside air flow rate increased the efficiency of the dual-duct system in comparison to the single-duct system during summer operation (Table 8-8 and Table 8-6). During the winter conditions, however, the dual-duct system did not show any advantage in either operation or efficiency. This proves that the dual-duct
configuration is going to use excessive fan power, and incapable of minimising the fresh air load (see discussion for the single-duct configuration).

8.2.3 “Fan-coil” benchmark systems performance

The performance of three variations of fan-coil-based benchmark configuration was also examined. Figure 8-6 gives a schematic diagram of the two fan-coil systems where one zone exhausts to the other. For the configuration “D2E” (as shown in Figure 8-6), the east zone is arranged to exhaust to the west zone; whereas for the configuration “D2F”, the order of zones is reversed. Figure 8-8 illustrates the third variation of the fan-coil configuration (“D2G”), in which the two zones are arranged in parallel. Note that the steam injectors in all three variations are marked redundant. This shows the optimisation was able to eliminate the need for humidification (in winter), by exploiting the tolerance. The optimum performance of the fan-coil systems is given in Table 8-9, Table 8-10, and Table 8-11. The summary of configuration efficiency of the systems can be found in Table 8-12.

![Figure 8-6 Fan-coil system in serial arrangement (east -> west)](image-url)
The common feature of the fan-coil systems is that the load of each zone is individually handled. The air-handling components, such as heating coil, cooling coil, and humidifier, are provided for each zone in the local recirculation path. This effectively decouples the zone load and the flow rate of supplied outside air. For configuration D2E and D2F, the two zones are arranged in a cycle, with separate fresh air paths provided to each zone. The cycle allows inter-zonal air flow which is considered beneficial. For example, in winter conditions when one zone has heat gain and the other has heat loss, inter-zonal circulation could offset the gain with the loss, therefore lower the overall load.

However, the ability of offsetting zone loads is constrained by the zonal temperature setting. Figure 8-7 explains the feasibility of inter-zone circulation. In Figure 8-7A, Zone1 has a 5kW loss of heat; Zone2 has a 5kW heat gain; therefore Zone1 requires heating and Zone2 requires cooling. Consider the temperature setting for Zone1 is 20°C, while the temperature for Zone2 is 25°C. Circulating exhaust air from Zone2 to Zone1 is effectively heating Zone1, whereas circulating from Zone1 to Zone2 cools Zone2. As a result, with a circulation flow rate at 0.94kg/s, the heat gain and loss are offset at the same time by circulating between the zones.

![Diagram](image)

**Figure 8-7 Feasibility of inter-zone circulation**

Now consider the configuration in Figure 8-7B, where the temperature of Zone1 is higher than Zone2, circulation between Zone1 and Zone2 is in fact increase the required heating and cooling capacity to maintain the zone conditions. Therefore the inter-zonal circulation has to be minimized.

For configuration D2G, the two zones are arranged in parallel. A centralised recirculation path is provided to achieve the preferable inter-zone air flow. The arrangement of the zones is illustrated in Figure 8-9. The Zone1 needs heating and the Zone2 needs cooling, whereas the temperature of Zone1 is lower than that of Zone2. A recirculation path providing 1.92kg/s of recirculated air at 22.5°C is able to offset the loads between zones.
From the optimum performance of the fan-coil systems (Table 8-9, Table 8-10, and Table 8-11), it is easy to conclude:

- With the fan-coil configurations, the input fresh air flow rate can be minimised in summer and winter conditions (with exception of winter at 14:00, which will be further explained)

- The total fan energy consumption is lower than the single-duct and dual-duct systems, in spite of the fact that the total air flow rate is higher. This is because that the air-handling components are located on the recirculation legs, therefore impose less restriction to the airflow

According to Table 8-4, in all winter conditions and the summer condition at 8:00, exhaust air should be made from the west zone (configuration D2F) in order to minimize the fresh air load. However, in the rest of summer conditions, exhaust air should relief from the
east zone (D2E). As a result, the configuration D2E is expected to perform better in the summer conditions at 14:00 and 17:00. This is proved in Table 8-9 and Figure 8-12. Comparing the results with other configurations, D2E’s energy consumption is significantly higher in the summer condition at 8:00. Apart from the higher fresh air load due to exhausting from the east zone, the operation required dehumidification and reheating for the east zone, because the moisture content of the mixture of fresh air and the air from the west zone exceeded the tolerance band.

Table 8-9 Optimum performance of the fan-coil system (D2E)

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Total Fresh Air</th>
<th>Total Circulated Air</th>
<th>Total Pressure</th>
<th>Total Circulation Consump.</th>
<th>Total Heating Duty</th>
<th>Total Cooling Duty</th>
<th>Total Humid. Duty</th>
<th>Total Energy Consum.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(kg/s)</td>
<td>(kg/s)</td>
<td>(Pa)</td>
<td>(kW)</td>
<td>(kW)</td>
<td>(kW)</td>
<td>(kW)</td>
<td>(kW)</td>
</tr>
<tr>
<td>Summer 08:00</td>
<td>0.128</td>
<td>1.056</td>
<td>75</td>
<td>0.107</td>
<td>1.486</td>
<td>-10.587</td>
<td>0</td>
<td>12.100</td>
</tr>
<tr>
<td>14:00</td>
<td>0.128</td>
<td>1.508</td>
<td>145</td>
<td>0.298</td>
<td>0</td>
<td>-8.992</td>
<td>0</td>
<td>9.289</td>
</tr>
<tr>
<td>17:00</td>
<td>0.128</td>
<td>1.780</td>
<td>196</td>
<td>0.486</td>
<td>0</td>
<td>-9.277</td>
<td>0</td>
<td>9.743</td>
</tr>
<tr>
<td>Winter 08:00</td>
<td>0.128</td>
<td>0.902</td>
<td>54</td>
<td>0.086</td>
<td>5.888</td>
<td>0</td>
<td>0</td>
<td>5.954</td>
</tr>
<tr>
<td>14:00</td>
<td>0.178</td>
<td>1.287</td>
<td>106</td>
<td>0.188</td>
<td>3.915</td>
<td>0</td>
<td>0</td>
<td>3.803</td>
</tr>
<tr>
<td>17:00</td>
<td>0.128</td>
<td>0.912</td>
<td>58</td>
<td>0.072</td>
<td>4.183</td>
<td>0</td>
<td>0</td>
<td>4.255</td>
</tr>
<tr>
<td>Spring/Fall 08:00</td>
<td>0.183</td>
<td>0.831</td>
<td>48</td>
<td>0.054</td>
<td>0.189</td>
<td>0</td>
<td>0</td>
<td>0.243</td>
</tr>
<tr>
<td>14:00</td>
<td>0.828</td>
<td>1.422</td>
<td>160</td>
<td>0.306</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.306</td>
</tr>
<tr>
<td>17:00</td>
<td>0.378</td>
<td>0.683</td>
<td>36</td>
<td>0.033</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.033</td>
</tr>
</tbody>
</table>

Weighted annual average: 4.610

Configuration D2F showed opposite performance to D2E (see Table 8-10). Its energy consumption was lower in the winter conditions and the summer condition at 8:00. However, in the other summer conditions, D2F consumes more energy than D2E.

Table 8-10 Optimum performance of the fan-coil system (D2F)

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Total Fresh Air</th>
<th>Total Circulated Air</th>
<th>Total Pressure</th>
<th>Total Circulation Consump.</th>
<th>Total Heating Duty</th>
<th>Total Cooling Duty</th>
<th>Total Humid. Duty</th>
<th>Total Energy Consum.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(kg/s)</td>
<td>(kg/s)</td>
<td>(Pa)</td>
<td>(kW)</td>
<td>(kW)</td>
<td>(kW)</td>
<td>(kW)</td>
<td>(kW)</td>
</tr>
<tr>
<td>Summer 08:00</td>
<td>0.128</td>
<td>1.604</td>
<td>196</td>
<td>0.426</td>
<td>0</td>
<td>-7.311</td>
<td>0</td>
<td>7.737</td>
</tr>
<tr>
<td>14:00</td>
<td>0.128</td>
<td>1.855</td>
<td>231</td>
<td>0.580</td>
<td>0</td>
<td>-9.448</td>
<td>0</td>
<td>10.026</td>
</tr>
<tr>
<td>17:00</td>
<td>0.128</td>
<td>1.934</td>
<td>233</td>
<td>0.609</td>
<td>0</td>
<td>-9.502</td>
<td>0</td>
<td>10.111</td>
</tr>
<tr>
<td>Winter 08:00</td>
<td>0.128</td>
<td>0.913</td>
<td>54</td>
<td>0.067</td>
<td>5.025</td>
<td>0</td>
<td>0</td>
<td>5.092</td>
</tr>
<tr>
<td>14:00</td>
<td>0.182</td>
<td>1.119</td>
<td>81</td>
<td>0.123</td>
<td>3.473</td>
<td>0</td>
<td>0</td>
<td>3.597</td>
</tr>
<tr>
<td>17:00</td>
<td>0.128</td>
<td>0.923</td>
<td>58</td>
<td>0.072</td>
<td>3.620</td>
<td>0</td>
<td>0</td>
<td>3.692</td>
</tr>
<tr>
<td>Spring/Fall 08:00</td>
<td>0.183</td>
<td>0.812</td>
<td>46</td>
<td>0.062</td>
<td>0.193</td>
<td>0</td>
<td>0</td>
<td>0.245</td>
</tr>
<tr>
<td>14:00</td>
<td>0.833</td>
<td>1.218</td>
<td>132</td>
<td>0.218</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.218</td>
</tr>
<tr>
<td>17:00</td>
<td>0.382</td>
<td>0.544</td>
<td>27</td>
<td>0.020</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.020</td>
</tr>
</tbody>
</table>

Weighted annual average: 4.189
The parallel arrangement of the zones in D2G showed performance compromise between D2E and D2F. The energy consumptions in all winter and summer conditions are between the values for D2E and D2F in the same condition. However, as for annual average consumption, D2G is better than both D2E and D2F, where zones are arranged in sequence.

### Table 8-11 Optimum performance of the fan-coil system (D2G)

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Total Fresh Air (kg/s)</th>
<th>Total Circulated Air (kg/s)</th>
<th>Total Pressure Loss (Pa)</th>
<th>Total Circulation Consump. (kW)</th>
<th>Total Heating Duty (kW)</th>
<th>Total Cooling Duty (kW)</th>
<th>Total Humid. Duty (kW)</th>
<th>Total Energy Consum. (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>08:00 0.128</td>
<td>1.685</td>
<td>207</td>
<td>0.487</td>
<td>0</td>
<td>-7.495</td>
<td>0</td>
<td>7.962</td>
</tr>
<tr>
<td></td>
<td>14:00 0.128</td>
<td>1.589</td>
<td>184</td>
<td>0.397</td>
<td>0</td>
<td>-9.107</td>
<td>0</td>
<td>9.504</td>
</tr>
<tr>
<td></td>
<td>17:00 0.128</td>
<td>1.685</td>
<td>270</td>
<td>0.990</td>
<td>0</td>
<td>-8.317</td>
<td>0</td>
<td>10.007</td>
</tr>
<tr>
<td>Winter</td>
<td>08:00 0.128</td>
<td>0.924</td>
<td>83</td>
<td>0.103</td>
<td>5.819</td>
<td>0</td>
<td>0</td>
<td>5.922</td>
</tr>
<tr>
<td></td>
<td>14:00 0.178</td>
<td>1.185</td>
<td>93</td>
<td>0.150</td>
<td>3.473</td>
<td>0</td>
<td>0</td>
<td>3.823</td>
</tr>
<tr>
<td></td>
<td>17:00 0.128</td>
<td>1.092</td>
<td>140</td>
<td>0.207</td>
<td>4.083</td>
<td>0</td>
<td>0</td>
<td>4.291</td>
</tr>
<tr>
<td>Spring/Fall</td>
<td>08:00 0.194</td>
<td>0.814</td>
<td>48</td>
<td>0.053</td>
<td>0.193</td>
<td>0</td>
<td>0</td>
<td>0.247</td>
</tr>
<tr>
<td></td>
<td>14:00 0.642</td>
<td>0.981</td>
<td>105</td>
<td>0.139</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.139</td>
</tr>
<tr>
<td></td>
<td>17:00 0.385</td>
<td>0.467</td>
<td>23</td>
<td>0.015</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.015</td>
</tr>
<tr>
<td></td>
<td><strong>Weighted annual average</strong></td>
<td></td>
<td></td>
<td><strong>4.185</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 8-12 Summary of configuration efficiency for fan-coil-based configurations

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Target capacity (kW)</th>
<th>West East (D2E)</th>
<th>East West (D2F)</th>
<th>Parallel (D2G)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Total capacity</td>
<td>Capacity overhead</td>
<td>Config. Efficiency</td>
</tr>
<tr>
<td>Summer</td>
<td>08:00 10.472</td>
<td>12.063</td>
<td>-3.587</td>
<td>74.0%</td>
</tr>
<tr>
<td></td>
<td>14:00 12.110</td>
<td>8.992</td>
<td>-0.040</td>
<td>100.3%</td>
</tr>
<tr>
<td></td>
<td>17:00 12.877</td>
<td>9.277</td>
<td>-0.070</td>
<td>100.0%</td>
</tr>
<tr>
<td>Winter</td>
<td>08:00 6.791</td>
<td>5.886</td>
<td>0.511</td>
<td>92.4%</td>
</tr>
<tr>
<td></td>
<td>14:00 3.039</td>
<td>3.615</td>
<td>2.303</td>
<td>48.7%</td>
</tr>
<tr>
<td></td>
<td>17:00 6.334</td>
<td>4.183</td>
<td>0.536</td>
<td>90.9%</td>
</tr>
<tr>
<td>Spring/Fall</td>
<td>08:00 0</td>
<td>0.189</td>
<td>0.189</td>
<td>100.0%</td>
</tr>
<tr>
<td></td>
<td>14:00 0</td>
<td>0</td>
<td>0</td>
<td>100.0%</td>
</tr>
<tr>
<td></td>
<td>17:00 0</td>
<td>0</td>
<td>0</td>
<td>100.0%</td>
</tr>
<tr>
<td>Annual average</td>
<td>5.042</td>
<td>4.420</td>
<td>0.807</td>
<td>90.7%</td>
</tr>
</tbody>
</table>

Table 8-12 further confirms the analysis in Table 8-14, with the calculated configuration efficiency values for each fan-coil configuration. For the configuration D2E, the west zone is arranged to exhaust through the east zone. High efficiency (>100%) is observed in the conditions at 14:00 and 17:00 in summer. For the configuration D2F, however, the high efficiency is achieved at 8:00 in summer, and at 8:00 and 17:00 in winter. The efficiency score exceeds 100% is because of the inaccuracy of the estimation of error in capacity due to
the presence of tolerance. The configuration D2G showed similar performance as D2F. This is because, although relief air exhaust from both zones, the east zone exhaust 2 times more than the west zone (0.096 kg/s vs. 0.032 kg/s) when outside air flow rate is minimised. This makes D2G behaves closer to D2E than to D2F.

Studying the results for the three variations of the fan-coil-based configurations, that each of them performs well in some but not all conditions, one question naturally arises: Is there a configuration that can perform well in all conditions? A potential design is a configuration that can invert the order of zones to suit each condition.

8.2.4 "Optimum" Benchmark System Performance

The conceptual optimum system configuration (D2H) is illustrated in Figure 8-10. A pair of inter-zonal paths is provided. The configuration resembles either D2E or D2F by closing one of the inter-zonal circulations.

![Figure 8-10 The conceptual optimum system configuration](image)

The optimal operation of this configuration confirms that it performs as good as the better configuration in each condition (see Table 8-13 and Table 8-14). High efficiency is achieved in all winter and summer conditions, except the winter condition at 14:00. Note that no configuration can achieve high efficiency in this condition. The reason is that the zone
temperature settings (22°C for the east zone and 20°C for the west zone) are preventing inter-zone load offset with recirculation (east zone has heat loss and west zone has heat gain). This condition was not considered in target capacity prediction, therefore lower target capacity was resulted.

### Table 8-13 Optimum performance of the conceptual optimum benchmark system

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Total Fresh Air (kg/s)</th>
<th>Total Circulated Air (kg/s)</th>
<th>Total Pressure Loss (Pa)</th>
<th>Total Circulation Consump. (kW)</th>
<th>Total Heating Duty (kW)</th>
<th>Total Cooling Duty (kW)</th>
<th>Total Humid. Duty (kW)</th>
<th>Total Energy Consum. (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>08:00 0.128</td>
<td>1.605</td>
<td>197</td>
<td>0.427</td>
<td>0</td>
<td>-7.311</td>
<td>0</td>
<td>7.739</td>
</tr>
<tr>
<td></td>
<td>14:00 0.128</td>
<td>1.511</td>
<td>146</td>
<td>0.300</td>
<td>0</td>
<td>-6.862</td>
<td>0</td>
<td>9.282</td>
</tr>
<tr>
<td></td>
<td>17:00 0.128</td>
<td>1.771</td>
<td>201</td>
<td>0.483</td>
<td>0</td>
<td>-9.275</td>
<td>0</td>
<td>9.758</td>
</tr>
<tr>
<td>Winter</td>
<td>08:00 0.128</td>
<td>0.918</td>
<td>56</td>
<td>0.068</td>
<td>5.624</td>
<td>0</td>
<td>0</td>
<td>5.692</td>
</tr>
<tr>
<td></td>
<td>14:00 0.182</td>
<td>1.119</td>
<td>82</td>
<td>0.124</td>
<td>3.473</td>
<td>0</td>
<td>0</td>
<td>3.597</td>
</tr>
<tr>
<td></td>
<td>17:00 0.128</td>
<td>0.923</td>
<td>58</td>
<td>0.072</td>
<td>3.220</td>
<td>0</td>
<td>0</td>
<td>3.892</td>
</tr>
<tr>
<td>Spring/Fall</td>
<td>08:00 0.193</td>
<td>0.812</td>
<td>47</td>
<td>0.052</td>
<td>0.193</td>
<td>0</td>
<td>0</td>
<td>0.245</td>
</tr>
<tr>
<td></td>
<td>14:00 0.842</td>
<td>0.961</td>
<td>94</td>
<td>0.125</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.125</td>
</tr>
<tr>
<td></td>
<td>17:00 0.385</td>
<td>0.467</td>
<td>21</td>
<td>0.013</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.013</td>
</tr>
</tbody>
</table>

Weighted annual average 4.088

### Table 8-14 Summary of system efficiency of the conceptual optimum configuration

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Target capacity (kW)</th>
<th>Total capacity (kW)</th>
<th>Tolerated error (kW)</th>
<th>Capacity overhead (kW)</th>
<th>Config. Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>08:00 10.472</td>
<td>7.311</td>
<td>3.149</td>
<td>-0.012</td>
<td>100.1%</td>
</tr>
<tr>
<td></td>
<td>14:00 12.110</td>
<td>8.982</td>
<td>3.078</td>
<td>-0.040</td>
<td>100.3%</td>
</tr>
<tr>
<td></td>
<td>17:00 12.877</td>
<td>9.275</td>
<td>3.351</td>
<td>-0.051</td>
<td>100.4%</td>
</tr>
<tr>
<td>Winter</td>
<td>08:00 6.791</td>
<td>5.624</td>
<td>1.176</td>
<td>0.009</td>
<td>99.9%</td>
</tr>
<tr>
<td></td>
<td>14:00 3.039</td>
<td>3.473</td>
<td>2.283</td>
<td>2.718</td>
<td>52.8%</td>
</tr>
<tr>
<td></td>
<td>17:00 5.334</td>
<td>3.920</td>
<td>1.387</td>
<td>-0.027</td>
<td>100.5%</td>
</tr>
<tr>
<td>Spring/Fall</td>
<td>08:00 0.0</td>
<td>0.193</td>
<td>0.872</td>
<td>0.193</td>
<td>100.0%</td>
</tr>
<tr>
<td></td>
<td>14:00 0.0</td>
<td>0</td>
<td>1.768</td>
<td>0</td>
<td>100.0%</td>
</tr>
<tr>
<td></td>
<td>17:00 0.0</td>
<td>0</td>
<td>0.703</td>
<td>0</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

Annual average 5.042 3.879 1.927 0.279 98.4%

### 8.3 Configuration synthesis

The experiments of synthesising HVAC configurations for the high load building have been performed for a fixed component set. The set of components is identical to those in the fan-coil-based configurations (D2E, D2F, and D2G). The component set consists of:
- Two heating coils (Heat)
Two cooling coils (Cool)
Two steam injection humidifiers (Steam)
Four pairs of flow-split (DIV) and merge (MIX) sections
Two Zones and one Ambient as the design required.

This component set gives a total of 120 problem variables, 21 discrete variables for the system topology, and 99 continuous variables for the system operation. There is one topology variable for the outlet connection of each component, including one for the ambient condition and the two zones; flow-split sections have two outlets and therefore there are two variables associated with flow-splits. There are 9 load conditions, and for each load condition, the problem variables are the capacity of the coils and humidifiers (6 variables), and 5 air flow rates (one for each flow-split and one for the outside air entering the system).

41 separate trial optimizations were conducted in two sets. The first set had a maximum number of generations set at 20,000, although some trials were manually terminated before 20,000 generations (due to time limitations on the use of the computer network used to perform the experiments). The maximum number of generations was fixed at 10,000 in the second set of trials, as it was evident from the first set of trials, that 10,000 generations was sufficient for convergence to take place. All optimisation parameters used in each trial, except the total number of generations, are identical to those listed in Table 5.3 (Chapter 5).

8.3.1 Consistency of Solutions

Table 8-15 lists the solutions that have been generated in each trial optimisation. The objective function values to the benchmark configuration are also listed. Comparing the results, the following figures can be summarised:

- In 27 out of 41 optimisations (66%), feasible solutions (Infeasibility = 0) that satisfy all the physical constraints and design requirements were found.

- 24 of the 27 feasible solutions (58% of all solutions) perform better than the single-duct benchmark system, in terms of annual average energy consumption. 5 generated solutions (12% of all) out-performed the dual-duct benchmark system, and 2 (5%) beat one of the fan-coil-based configurations.
The annual average energy consumption of the best generated configuration (4.34kW) is 7% higher than that of the conceptual optimum configuration (4.06kW). The top synthesised configuration is thus considered "near optimum".

Table 8-15 Synthesised solutions from 41 experiments

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Best solution found</th>
<th>Total number of generations</th>
<th>Total number of topologies evaluated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Infeasibility</td>
<td>Objective</td>
<td></td>
</tr>
<tr>
<td>D2H</td>
<td>0</td>
<td>4.06</td>
<td>-</td>
</tr>
<tr>
<td>D2G</td>
<td>0</td>
<td>4.18</td>
<td>-</td>
</tr>
<tr>
<td>D2F</td>
<td>0</td>
<td>4.19</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>4.34</td>
<td>20,000</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>4.45</td>
<td>20,000</td>
</tr>
<tr>
<td>D2E</td>
<td>0</td>
<td>4.61</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>4.78</td>
<td>20,000</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>4.79</td>
<td>18,897</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>5.09</td>
<td>10,000</td>
</tr>
<tr>
<td>Dual-Duct</td>
<td>0</td>
<td>5.13</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>5.26</td>
<td>10,000</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>5.42</td>
<td>10,000</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>5.58</td>
<td>20,000</td>
</tr>
<tr>
<td>9</td>
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<td>5.85</td>
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<td>14,746</td>
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<td>0</td>
<td>7.38</td>
<td>16,401</td>
</tr>
<tr>
<td>Single-Duct</td>
<td>0</td>
<td>7.42</td>
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<td>25</td>
<td>0</td>
<td>7.62</td>
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</tr>
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</tr>
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<td>0</td>
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<td>8.53E-09</td>
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<td>1.18E-06</td>
<td>6.02</td>
<td>10,000</td>
</tr>
<tr>
<td>30</td>
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<td>7.29</td>
<td>9,148</td>
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<td>31</td>
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<td>7.16</td>
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<td>39</td>
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</tr>
<tr>
<td>40</td>
<td>5.33E-05</td>
<td>15.46</td>
<td>10,000</td>
</tr>
<tr>
<td>41</td>
<td>1.81E-04</td>
<td>16.61</td>
<td>10,000</td>
</tr>
</tbody>
</table>
Combining the 41 optimisations, about $2.63 \times 10^7$ topologies in total have been evaluated. However, comparing to the size of search space at $3.19 \times 10^{18}$ possible topologies, only 8 trillionth of the search space has been explored.

Inspecting the 34% of the trials (14 from 41) that have failed to find feasible solutions, the system operation of the top solution in each search has been optimised. The infeasibility was a result of the constraint on the supply air conditions not being met. It is therefore suggested that the infeasibility was due to the configuration being inherently unable to meet the zone loads.

Given the multi-modality of the configuration synthesis problem, it is a challenge for the optimisation algorithm to avoid converging on a local optimum. Despite the efforts in developing problem-specific operators to encourage topological exploration, single optimisation with the present algorithm is still subject to premature convergence. This gives the results of 34% of trials got stuck with an inherently infeasible configuration. Multiple runs of optimisation on the same problem, each of which starts with a random population, are required to ensure a near-optimum solution.

Table 8-16 shows the convergence of the optimisation trials in which feasible solutions were found. For these trials, the initial feasible solution was found with a mean of 1,722 generations. Fast convergence followed the finding of a feasible solution, with a 38% reduction in the mean objective function value after a further 500 generations (from 12.93 kW to 8.06 kW); a further 11% reduction in the mean objective function value was achieved by the final population (6.57 kW). However, only 4.2% reduction was achieved after 5,000 generations (6.86 kW to 6.57 kW), which suggests that convergence had started before 5,000 generations.

The last column in Table 8-16 shows the total number of evaluations that had been performed on the top configuration. These evaluations were performed on the solutions sharing the same topology but having different operational parameters. As the Ageing factor in the optimisation was set to 20, which means each topology can not be evaluated for more than 20 times of total number of generations without getting penalized. The data in Table 8-16 shows that, for most of the top topologies in the final solutions, the number of evaluations have reached maximum. It can be assumed their Operation variables have been sufficiently optimised. The only exception here is case 6 and case 15. The numbers of evaluations in these cases are lower than the 20,000 quota; therefore the system operations of these topologies might be further optimised if EA were allowed to run for longer time.
It can be concluded from the results that the optimization is able to synthesize systems that have a comparable performance to established systems. Multiple runs of the optimization are required, however, in order to find (near) optimum system configurations.

8.3.2 Solution Optimality

The best solution found during all trial optimizations has an objective function value that is within 7% of the conceptual optimum systems objective function value (4.32kW compared to 4.06kW). The objective function value is 15% lower than that of the dual-duct system and 41% lower than the single-duct system objective function. Therefore, the synthesized system can be considered to be near optimal for the given circumstances.

The topology of the best synthesized configuration is illustrated in Figure 8-11. The steam humidifiers (shaded gray), are not used at any load condition. The system conforms to the hypothesis that an optimum system configuration is one that has separate HVAC compo-
nents for each zone, and that each zone has an independent recirculation air path for the zone extract air.

![Diagram](Image)

Figure 8-11 The best synthesized system configuration

Table 8-17 Optimum performance of the best synthesized System

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Total Fresh Air (kg/s)</th>
<th>Total Circulated Air (kg/s)</th>
<th>Total Pressure Loss (Pa)</th>
<th>Total Circulation Consump. (kW)</th>
<th>Total Heating Duty (kW)</th>
<th>Total Cooling Duty (kW)</th>
<th>Total Humid. Duty (kW)</th>
<th>Total Energy Consum. (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>08:00 0.128 1.581 205 0.438 0 -7.315 0 7.753</td>
<td>Winter 08:00 0.128 0.854 58 0.067 5.638 0 0 5.706</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>14:00 0.128 1.855 247 0.621 0 -9.449 0 10.070</td>
<td></td>
<td>17:00 0.128 1.988 282 0.760 0 -9.490 0 10.250</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>14:00 0.193 1.565 172 0.365 3.777 0 0 4.141</td>
<td></td>
<td>17:00 0.132 1.244 140 0.236 4.022 0 0 4.258</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>08:00 0.195 0.937 70 0.069 0.195 0 0 0.284</td>
<td></td>
<td>14:00 0.823 1.506 218 0.445 0 0 0 0.445</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>17:00 0.379 0.650 41 0.036 0 0 0 0.036</td>
<td></td>
<td></td>
<td>Weighted annual average</td>
<td>4.339</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In comparison to the conceptual optimum system configuration (Figure 8-10), and the derivatives of fan-coil system (Figure 8-6 and Figure 8-8), the synthesised system has insufficient capability of circulating air between zones. Consider the circuit for the east zone between point A and point B in Figure 8-11, the amount of (fresh) air that goes into the circuit (at point A) equals the amount of air that comes out of it (at point B). When minimum
fresh air is preferred during summer and winter seasons, the amount of air that can be transported from the east zone to the west zone equals the amount of fresh air supplied to the east zone. In a condition when inter-zone circulation is beneficial, a trade off will be made between increasing inter-zone circulation and minimising fresh air load. This was clearly what happened with the operation in winter condition at 17:00 (see Table 8-17).

Also the synthesized system is sub-optimal in that air can only be extracted from the west zone. Therefore, similar to the benchmark configuration D2F, in summer conditions at 14:00 and 17:00, it is unable to reduce fresh air load by minimising the enthalpy difference between extracted air and fresh air. Further, the east zone coils are located in the extract duct rather than the lower air flow rate recirculation duct, which explains the relatively high circulation cost, especially in swing seasons (see Table 8-17).

Table 8-18 summaries the configuration efficiency of the synthesised system. The results resembles those of the second fan-coil configuration (D2F), though slight worse in the winter conditions. The possible reasons have been indicated as above. It is again confirming that the synthetic system has a near-optimum configuration, the sub-optimality being due to the inability of the system to allow air from the west zone to be exhausted through the east zone. The optimality of the system could be further improved by moving the east zone heating and cooling coil to the east zone recirculation ducts (where the air flow rate and pressure drop is likely to be lower).

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Target capacity (kW)</th>
<th>Total capacity (kW)</th>
<th>Tolerated error (kW)</th>
<th>Capacity overhead (kW)</th>
<th>Effciency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>06:00</td>
<td>10.472</td>
<td>7.315</td>
<td>3.155</td>
<td>-0.003</td>
<td>100.0%</td>
</tr>
<tr>
<td>14:00</td>
<td>12.110</td>
<td>9.449</td>
<td>3.786</td>
<td>1.125</td>
<td>91.5%</td>
</tr>
<tr>
<td>17:00</td>
<td>12.677</td>
<td>9.480</td>
<td>3.696</td>
<td>0.509</td>
<td>96.1%</td>
</tr>
<tr>
<td>Winter</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>06:00</td>
<td>6.791</td>
<td>5.838</td>
<td>1.133</td>
<td>0.010</td>
<td>99.6%</td>
</tr>
<tr>
<td>14:00</td>
<td>3.039</td>
<td>3.777</td>
<td>2.548</td>
<td>3.286</td>
<td>48.0%</td>
</tr>
<tr>
<td>17:00</td>
<td>5.334</td>
<td>4.022</td>
<td>1.490</td>
<td>1.416</td>
<td>99.7%</td>
</tr>
<tr>
<td>Spring/Fall</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>08:00</td>
<td>0</td>
<td>0.195</td>
<td>0.806</td>
<td>0.196</td>
<td>100.0%</td>
</tr>
<tr>
<td>14:00</td>
<td>0</td>
<td>0</td>
<td>1.835</td>
<td>0</td>
<td>100.0%</td>
</tr>
<tr>
<td>17:00</td>
<td>0</td>
<td>0</td>
<td>0.745</td>
<td>0</td>
<td>100.0%</td>
</tr>
<tr>
<td>Annual average</td>
<td>5.042</td>
<td>3.989</td>
<td>2.087</td>
<td>0.531</td>
<td>93.2%</td>
</tr>
</tbody>
</table>
Table 8-19 shows the comparison of benchmark systems and the synthesised systems. The second best synthesised configuration is also included in the comparison. The schematic of the second best generated system is shown in Figure 8-12.

### Table 8-19 System efficiency comparison for the synthesized systems and the benchmark Systems

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Energy Consumption (kW)</th>
<th>Single-Duct</th>
<th>Dual-Duct</th>
<th>Fan-coil</th>
<th>Optimum</th>
<th>Synth. 1</th>
<th>Synth. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>D2E</td>
<td>D2F</td>
<td>D2G</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>08:00</td>
<td>08:00</td>
<td>08:00</td>
<td>08:00</td>
<td>08:00</td>
<td>08:00</td>
</tr>
<tr>
<td>Summer</td>
<td></td>
<td>9.34</td>
<td>9.51</td>
<td>12.16</td>
<td>7.74</td>
<td>7.96</td>
<td>7.74</td>
</tr>
<tr>
<td>14:00</td>
<td></td>
<td>28.54</td>
<td>13.01</td>
<td>9.29</td>
<td>10.03</td>
<td>9.50</td>
<td>9.29</td>
</tr>
<tr>
<td>17:00</td>
<td></td>
<td>20.46</td>
<td>12.67</td>
<td>9.74</td>
<td>10.11</td>
<td>10.01</td>
<td>9.76</td>
</tr>
<tr>
<td>Winter</td>
<td></td>
<td>5.99</td>
<td>6.09</td>
<td>5.95</td>
<td>5.69</td>
<td>5.92</td>
<td>5.69</td>
</tr>
<tr>
<td>14:00</td>
<td></td>
<td>4.68</td>
<td>4.77</td>
<td>3.80</td>
<td>3.60</td>
<td>3.62</td>
<td>3.60</td>
</tr>
<tr>
<td>17:00</td>
<td></td>
<td>4.33</td>
<td>4.40</td>
<td>4.26</td>
<td>3.99</td>
<td>4.29</td>
<td>3.99</td>
</tr>
<tr>
<td>Spring/Fall</td>
<td></td>
<td>0.28</td>
<td>0.29</td>
<td>0.24</td>
<td>0.25</td>
<td>0.25</td>
<td>0.24</td>
</tr>
<tr>
<td>14:00</td>
<td></td>
<td>0.26</td>
<td>0.27</td>
<td>0.31</td>
<td>0.22</td>
<td>0.14</td>
<td>0.12</td>
</tr>
<tr>
<td>17:00</td>
<td></td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Annual</td>
<td></td>
<td>7.42</td>
<td>5.13</td>
<td>4.61</td>
<td>4.19</td>
<td>4.18</td>
<td>4.06</td>
</tr>
</tbody>
</table>

*Optimum, Synth. 1, Synth. 2: Marked in blue and red for the best and worst consumptions in each operating condition respectively, with the runners-up in bold. The lower consumption values achieved by a synthesised configuration are marked bold italic.*

#### Figure 8-12 The second best synthesised configuration

The best (lowest) and worst (highest) consumptions in each operating condition have been marked blue and red respectively, in Table 8-19. The runners-up are bolded. The lower consumption values achieved by a synthesised configuration are marked bold italic. Apparently the fan-coil systems with zones arranged in sequence (D2E and D2F) perform the best.
in most of the operating conditions; whereas the conceptual optimum configuration displayed either lowest or second lowest energy consumption in all conditions. As the conceptual optimum system is slightly more complex than the fan-coil derivatives, in same circumstance it tends to consume more energy in circulation. The synthesised configurations showed competitive performance in the summer condition at 8:00 and winter conditions at 8:00 and 17:00. However, they suffered from the highest circulation cost in the intermediate seasons, due to the sub-optimal arrangement of components they have. In general, the performance of the synthesised configurations is comparable to that of the benchmark configurations.

8.4 Discussion

As the results from the experiments showed, the present approach for configuration synthesis was able find near-optimum solutions with multiple optimisation runs. The results indicated that the implemented optimisation algorithm, especially for topology search, was unable to avoid converging to local optima. In this section, the role of the problem-specific operators in topology exploration and the possibility of seeding are discussed.

8.4.1 Topology exploration

It has been observed in the 41 trial optimisations (Table 8-16), the searches started to converge at about 5,000 generations. Neither the objective function, nor the infeasibility score of the top solution improved significantly after this. However, the top solution in the final generation unnecessarily shared the same topology as the top solution at 5,000th or 10,000th generation. Meanwhile, there are usually multiple feasible configurations having similar objective function values in the final population. These facts suggest the topologies have been searched by the algorithm, although the search is confined in the neighbourhood area of the configuration once found as local optimum. An example was taken from the run set 1, number 19. Figure 8-13 shows the progress of the top solution since generation 5,000.

The configuration in Figure 8-13(A) is rather similar to the single-duct benchmark system, except the presence of local circulation for the east zone. As a result, the energy consumption is slightly better than the single-duct system. In the next 5,000 generations, the search algorithm managed to move a cooling coil to the parallel branch to the other cooling coil (Figure 8-13B), which changed the working condition of the cooling coils and resulted in marginal savings on both coil capacity and fan cost.
Chapter 8 Example optimisation: two-zone system

(A) Best topology after 5,000 generations, with energy consumption of 6.86kW

(B) Best topology after 10,000 generations, with energy consumption of 6.80kW

(C) Best topology at the final (18,897) generation, with energy consumption of 4.79kW

Figure 8-13 Example of the progress of topology search
By the end of the search, one cooling coil and one heating coil were moved to the exhaust branch for the east zone; therefore the east zone has its own air-handling unit and local circulation. Although only one of the two zones was locally conditioned, the system as whole outperformed the benchmark systems with centralized air-conditioning (single-duct and dual-duct configurations).

In the 18,897 generations of search, a total of 766,857 different topologies have been evaluated. However, the top solutions in each generation after 5,000 remain similar to each other. In the example in Figure 8-13, only one or two components were moved each time. These top solutions are believed belonging to the same neighbourhood; and the search for the optimum topology was unable to go beyond the boundary of the neighbourhood.

Three facts contribute to the behaviour the topology exploration. Firstly, the configuration synthesis problem is a multi-modal optimisation problem. A configuration is evaluated by the objective function and the constraint function. The topology of the configuration has to be feasible (strongly connected and solvable), before its operation can be evaluated. Also because the optimisation of the operations of the configuration is highly constrained and non-linear, it is hard to solve. As a result, it takes a large amount of function evaluations over many generations of evolution, to achieve certain optimality of a configuration. On the other hand, any changes to the established topology tend to severely degrade the optimality of the configuration. Consequently, this is likely to be discouraged during the evolutionary process.

Secondly, the topology-specific operators developed in this research incline to explore within neighbourhood. The topology-specific operators, such as the Swap Components Mutation and the Adjacent Components Crossover, are designed to maintain the integrity of the topologies. The strategy used is to bring small changes to the topology at each time. As a result, the chances for a topology producing offspring that belong to different neighbourhood are diminished.

And finally, the Ageing operator is designed to encourage exploring different topologies. It is incapable of identifying the boundaries of neighbourhoods; therefore it can not help cross-neighbourhood exploring. The Ageing operator discriminates configurations by the encoding of the topology string. However, as discussed in Section 5.1.4 (Chapter 5), similar topologies can have very different encodings. The similarity between topologies, or the neighbourhood of topologies, is difficult to define. Further study is needed to identify the neighbourhoods, and encourage cross-neighbourhood search.
8.4.2 Seeding

Given the fact that a search started with a random population has 34% of chance to fail in finding a feasible solution (Table 8-15), and that the implemented approach is capable of exploring topologies effectively within the neighbourhood, it is intuitive to investigate if a search seeded with an established system is more likely to deliver feasible and better-performing configurations.

The approach adopted here is to seed the initial population with the dual-duct system, the operation of the system having first been optimized; the remainder of the population is randomly initialized. Since the randomly initialized solutions generally have a performance much worse than the optimized seed solution, the search will quickly drift towards the dual-duct solution and explore its neighbourhood. The parameters of the optimisation were adjusted in order to increase the probability that the top solution would be selected for mating and mutation. This was achieved through reducing the population size, increasing the “selective” pressure in the tournament selection, and decreasing the probability of mutation. In comparison to the values in Chapter 5, Table 5.3, the population size was set to 500, the tournament selection to “1 from 4”, the probability of topology mutation to 1% and 5% for flow rates and capacity. Each trial optimization was stopped after 10,000 generations.

25 separate trial optimizations were performed (Table 8-20). The average objective function value of the solutions is 1.2% lower than that of the dual-duct system (5.068 kW compared to 5.131 kW). The best solution has an objective function value that is 9.2% better than that of the dual-duct system (4.659 kW compared to 5.131 kW). However, the best solution still has an objective function value that is 14% higher than that of the conceptual optimum system (4.649 kW compared to 4.058 kW), and is 7% higher than the objective function of the best system synthesized by the randomly initialized search (4.649 kW compared to 4.339 kW).

It can be concluded that the use of seeding with the present approach will exploit the neighbourhood of the seed solution. In this way, it is possible to guide the search to a certain direction, or within a limited area. The potential application is to “synthesis configurations that are similar to a known solution, but with improved performance”. It is more reliable in finding good solutions, although the optimality of the final result is likely to depend on the choice of seed. Multiple trials are also required to ensure a better solution being found.
Table 8-20 Summary of the trials of the Seeded Search

<table>
<thead>
<tr>
<th>Run</th>
<th>First seen Improvement</th>
<th>Final Generation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Generation</td>
<td>Objective (kW)</td>
</tr>
<tr>
<td>1</td>
<td>443</td>
<td>5.130</td>
</tr>
<tr>
<td>2</td>
<td>2,528</td>
<td>5.130</td>
</tr>
<tr>
<td>3</td>
<td>194</td>
<td>5.130</td>
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<tr>
<td>4</td>
<td>842</td>
<td>5.114</td>
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<tr>
<td>5</td>
<td>791</td>
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</tr>
<tr>
<td>6</td>
<td>1,673</td>
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<td>8</td>
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<td>10</td>
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<td>5.130</td>
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<td>649</td>
<td>5.130</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>5.115</td>
</tr>
<tr>
<td></td>
<td>Dual-Duct system</td>
<td>5.130</td>
</tr>
</tbody>
</table>

8.5 Summary

In this chapter, experiments have been set up to reveal the capability and characteristics of the implemented optimisation approach for HVAC system configuration synthesis. A design case was prepared for a 2-zone building situated in continental climate, as well as having high solar gains and internal gains. The design requirements for the 2 zones are deliberately made different. In some conditions, the conflicting demands of the two zones require the HVAC system to be able handle the zones separately; whereas in some other conditions, inter-zonal air flow provided by the configuration would be preferable.

A set of 6 benchmark system configurations were used to provide references to the synthesised designs, as well as to help understanding the design requirements.
benchmark configurations are derived from the single-duct VAV and the dual-duct VAV systems, respectively. Three benchmark configurations are based on fan-coil units, whereas the circulations between zones are arranged differently. The last benchmark is the so-called "conceptual optimum" configuration, in which a pair of inter-zonal circulation paths are provided. As a result, the conceptual optimum configuration can act as either of the fan-coil-based systems to suit the particular design conditions.

Experiments of configuration synthesis were then carried out, with 41 separate trials in total. Each trial optimisation has been initialized with a random population. The results from the 41 trials show that, the implemented approach was able to find "near optimum" solutions for a given design circumstances. However, multiple optimisations are needed to ensure a good solution to be found, as a single optimisation may prematurely converge to an infeasible solution. Experimental results showed insufficiency of the present algorithm in exploring the topological space. The possible reasons have been discussed.

The potential of starting the optimisations with a random population seeded with established solutions has also been studied. Experimental results showed, although with seeding, feasible solutions are guaranteed at the end of the optimisation, the search is likely being confined within the neighbourhood area of the seed; therefore multiple optimisations are still required to deliver near-optimum solutions.
Chapter 9

Conclusions and Future Work

The HVAC system configuration is a conceptual design of the HVAC system, including the employed components, the arrangement of airflow network, and the control strategy and set points for different operation conditions. The automatic design synthesis approach for the HVAC system configurations is to search for the optimum design with an optimisation algorithm. In order to establish the approach, a number of issues have to be addressed.

Firstly, the optimisation problem for HVAC system configuration synthesis has to be defined. The scope of this research has been defined as the secondary HVAC system with a limit number of components. The HVAC system configuration was represented as a set of components, an airflow network topology, and a number of control set points for the assumed supervisory control strategy. A static configuration model has also been developed in order to evaluate the energy performance of the solutions. A number of optimisation variables have been identified; and the optimisation problem was defined as to minimise the objective function (annual energy consumption), which subjected to design constraints.

Secondly, an Evolutionary Algorithm-based optimisation method was developed to solve the optimisation problem for configuration synthesis. The configuration problem is a multi-level problem, because the definition of the topology is dependent on the set of selected
components, whereas the control set points only becomes valid when the topology is defined. On the other hand, the performance of the configuration is assessed with its optimum operation; therefore the control set points have to be optimised for each configuration solution, before the configuration can be optimised. In this research, a simultaneous approach has been developed. All optimisation variables of the configuration were encoded into an integrated genotypic data structure. Evolutionary operators were developed to search the topological space (topology) and parametric space (control set points) at the same time.

This chapter reviews the achievements and limitations of the research, and suggests directions of future developments and applications.

9.1 Achievements

Automatic configuration design synthesis with optimisation methods is a new concept in engineering. With the result of the present research, the concept has been proved possible in the field of HVAC system design. As an initiative proof-of-concept attempt, the development of the HVAC system configuration synthesis method has achieved most of the objectives outlined in Chapter 1. These objectives include: to study the HVAC configuration design from the energy respect; to formulate the optimisation problem for configuration design synthesis; to develop and implement the optimisation method for configuration synthesis; and, to validate and analyse the implemented approach. This section summarises the achievements of this study.

9.1.1 HVAC configuration and energy consumption

From the energy point of view, an HVAC system configuration can be represented as a set of components (defined by psychrometric processes), an airflow network topology (defined as a directed graph with components as its nodes and airflows as its edges), and a control strategy with set points. Such abstraction provides a uniform way to describe various designs of HVAC system configurations; meanwhile, it is sufficient for energy and psychrometric analysis of configurations. Most of the existing HVAC system configurations can be represented this way (see Appendix A). The task for configuration design synthesis is to find the optimal set of components, the ideal topology of the airflow network, and the best control strategy and optimum set points for various operation conditions. Since the optimum supervisory control strategy is normally able to deliver better performance than localized
control strategies, it is taken as the control strategy by default; only the optimum set points
for supervisory control need to be identified.

With energy and psychrometric analysis, it can be concluded that the configuration de-
sign has significant impacts on the energy consumption of the HVAC system. Energy waste
can be caused by sub-optimal configuration designs in three ways: simultaneous cooling and
heating caused by the limitations of component performance; being unable to minimise fresh
air load; and inability of exploiting inter-zone load compensation (Chapter 3, section 3.2). It
was indicated that a conceptual optimum configuration has to be able to: handle the load of
each zone separately; effectively use alternative air-handling processes and mixing; re-
circulate air between different zones; minimize intake volume of fresh air and its enthalpy
difference to the exhaust air; and minimize fan energy consumption.

9.1.2 Configuration synthesis – the approach

The approach to optimum configuration design synthesis is to formulate the HVAC sys-
tem configuration design problem as an optimisation problem, and apply an optimisation
method to search for the optimum solution of the problem. The following issues have been
addressed in this study:

- Development of numerical models for performance simulation of HVAC system con-
  figurations.

- Formulation of the optimisation problem, including the problem variables, the objec-
  tive function, and the constraint functions, for configuration synthesis.

- Development of the genotypic encoding of the configuration problem, and the im-
  plementation of the Evolutionary Algorithm-based optimisation method.

- Development of the problem-specific algorithm operators to enhance the perform-
  ance of the search algorithm.

HVAC configuration models that are suitable for automatic design synthesis have been
developed in this research. The configuration model consists of component models that
define the psychrometric and airflow-related behaviour of each component. Graph methods
are used to solve the operation conditions of the configuration.
The formulation of the optimisation problem for configuration synthesis includes the identification of problem variables, the evaluation of optimisation objective, and the assessment of constraint violations. For the HVAC system configuration problem, the optimisation variables include the component set, the topology, and the control set points (component duties and flow rates) for each of the operation conditions. The objective function of configuration synthesis is defined as the annual average energy consumption based on a number of static load conditions. The constraints for the optimisation include topological constraints that ensure the configuration is connected and fit for air circulation, and the operation-related constraints that represent the performance limits of the components, and the design requirements for the conditioned spaces.

The configuration synthesis problem is a multi-level optimisation problem. On the upper level, optimum set of components and topology design is to be searched. On the lower level, the operation (control set points) of each configuration is to be optimised. Evaluation of the candidate configuration (components and topology) is based on the optimal operation condition. The method adopted in this research is to use Evolutionary Algorithm to solve the multi-level problem simultaneously.

Firstly, a Genome encoding has been developed to represent the problem variables in a data structure. The Genome for HVAC system configuration contains the ComponentSet, the Topology, and the Operation chromosomes. The definition of the genes in the Topology and Operation chromosomes is dependent on the ComponentSet chromosome. The Hyper reproduction operator scheme has been developed to provide effective operating on the configuration Genome.

Problem-specific algorithm operators have been developed for the search of optimum configuration design. These problem-specific operators include the topology-oriented "swap components mutation" and "adjacent component crossover", the flow-duty-oriented "shift duties mutation" and "centre-of-gravity crossover", and the "Ageing" operator for topology exploration. The benefit of the operators has been approved by the evaluation.

9.1.3 Validation and results – the proof-of-concept

The implemented approach has been validated with two tests. The first test was to synthesis a simple system configuration for a single zone building. The optimised results were compared with the results from the exhaustive search. It is proved that the global optimum
solution has been identified by the optimisation approach, with much fewer function evaluations comparing to the exhaustive search.

The second test was to synthesise HVAC system configurations for a two-zone building, for which free cooling was considered to be sufficient in all design conditions. This test has proved the ability of the optimisation approach in identifying redundant components and moving them to less flow-restricting locations, therefore minimizing overall system energy consumption.

Full-scale proof-of-concept experiments were then set up. The configurations of HVAC system for a two-zone building were synthesised using the developed approach. The requirements of the two air-conditioned zones are deliberately made different, in order to reveal the capability of the optimisation algorithm in exploiting full potential of the HVAC system. 41 optimisation trials were carried out; the performance of the synthesised configurations was compared to that of the 6 benchmark configurations (including those of established systems and the conceptual optimum configuration described in Chapter 3). The configuration synthesis approach was able to generate near-optimum solutions, whose performance is comparable to the best of established systems. Due to the large size of the search space, however, multiple optimisations were required to guarantee a near-optimum solution being found. This also indicates the need for further improvement of the algorithm in topology exploration.

9.1.4 Conclusion

The main conclusions of this study can be summarised as "the (near) optimum configuration design of the secondary HVAC system can be synthesised with the use of an appropriate optimisation method". More specifically,

- the configuration of HVAC system can be represented as a set of components, a topology, and a control strategy with set points;
- configuration synthesis is to find optimal combination of components, topology, and control strategy that minimises certain objective function(s), while subject to a number of design constraints;
- the objective function (annual energy consumption in this research) and the constraint functions (topology connectivity, performance limitation of components, and
zone design requirements) can be evaluated with the use of configuration performance model;

- the optimisation variables for the components, the topology, and the control strategy (set points) can be encoded into hierarchical genotype, where the definitions of the genes in the Topology chromosome and the Operation chromosomes are determined by the ComponentSet chromosome;

- the Evolutionary Algorithm can be implemented to search in the topology space and the system operation space simultaneously;

- problem-specific algorithm operators (topology-specific and operation-specific reproduction operators, and the Ageing operator) can be implemented to enhance the performance of evolutionary optimisation;

- the overall concept of this research has been proved with three example optimisations: the developed configuration synthesis approach was able to identify the global optimal solution for a simple single-zone system; it is capable of minimising both component duties and fan energy consumption and producing better configurations than a conventional solution for a 2-zone low load building; and it is able to generate near optimum solutions for a 2-zone high load building, in which the operation conditions are complex and harder to solve.

### 9.2 Limitations and future research

The research described in this thesis has developed an optimisation approach for synthesising conceptual configuration designs for HVAC systems. As a proof-of-concept, however, this study opens up more questions than those it has solved. First of all, the HVAC systems in the real world are more complex than the simplified secondary air system model considered in this research. A real HVAC system may consist of large array of sub-systems and components. It is also dynamically interacting with the building, the occupants, and other building energy systems. Extensions to the present approach are required to make it useful for real design applications. Future research can be envisaged in two directions: the development of system models, and the development of optimisation methods for complex engineering system designs.
HVAC and building system model

The configuration synthesis problem for HVAC systems is regarded as more complex and harder to solve than many of the optimisation problems for HVAC design. Simplifications and abstractions have been made in this research, especially to the HVAC system configuration model.

Firstly, the configuration model is based on idealistic psychrometric models for the components. For example, the modelled cooling process has two sections of process line on the psychrometric chart (Chapter 4, Figure 4-4). The first section is completely sensible cooling, until the temperature reaches the dew point, after which, the process follows the saturation line. This process can hardly be realized using a typical cooling coil. Other idealistic assumptions include zero air infiltration or leakage, and zero unwanted heat gain or loss, in the system, realistic and detailed models are needed for synthesising realizable configurations.

Secondly, only a small number of component types were considered in this research. Other types of air-handling components, such as evaporative cooling, desiccant dehumidification, and heat recovery, are excluded. As a result, the conclusions regarding the optimality of configurations, and the conceptual optimum configuration, are limited to using the present list of components. Also in this research, the fan energy consumption was estimated using fix airflow resistance factors of the components. The absence of fan and ductwork models makes the estimation of fan energy consumption inaccurate. Especially when trade-offs are to be made between coil duties and the fan energy consumption, the resulting configuration may be not optimal for the real circumstances. This again indicates the requirement for detailed models that are capable of simulating realistic performance of the components.

Finally, the configuration of the secondary HVAC system has been studied in isolation to the building and other systems (e.g. the primary system). The boundary of the secondary system to the building and the primary system has been defined by input/output of thermal energy and moisture. In this way, the annual operation of the secondary HVAC system can be discretized; and static models can be used to study the “snapshots” of operation conditions. In order to synthesise the optimum design for a real world application, however, the dynamics of the HVAC system, and its interaction with the building and other systems, have to be considered. Dynamic models of the secondary HVAC system, the building, and other relevant systems, are required.
In summary, the HVAC system is an integral part of the dynamic building system. In order to achieve the optimum design of HVAC system, detailed and dynamic models of its components and associated building systems are needed. This also means more optimisation variables, therefore a larger and more complex search space. The optimisation algorithm has to be further developed to meet the demand.

**System-level optimisation methods**

There are two major limitations in this research with regard to the implementation of the optimisation algorithm. Firstly, the ComponentSet chromosome in the HVAC configuration genome has been deliberately chosen, and remains fixed during the optimisation. This was required as a simplification to remove the need of synchronization of changes between the member chromosomes (see Chapter 5, 5.1.2). It is arguable that, by choosing the maximum set of components at the start of optimisation, and removing the redundant components afterwards, the same optimum solution can be found as that by using a variable ComponentSet implementation. Although the size of search space remains the same for the fixed or variable ComponentSet approaches, the landscape of the search space can be very different.

The fixed ComponentSet approach (as adopted in this research) starts the search with maximum size of the topology space. For the variable ComponentSet approach, on the contrary, the search space for topology changes accordingly, despite that it is always no larger than that for the fixed-length approach. Since the size of topology search space is in order of \(O(N!)\), where \(N\) is the number of components, a shorter ComponentSet chromosome means a much smaller topology space. If there is the optimum topology in the smaller search space, it has higher chance to be found. This suggests a variable ComponentSet approach may have better optimisation performance than the fixed-length alternative. The main difficulty for the variable-length implementation, however, is to develop an efficient synchronization method for the member chromosomes in the genome. This deserves further investigation in the future.

The second limitation of the developed optimisation algorithm is its lack of ability in searching beyond topology neighbourhood (see Chapter 5, 5.1.4, and Chapter 8, 8.4.1). The Ageing operator developed in this research was able to prevent pre-mature convergence to a single topology. The convergence to a neighbourhood, however, can not be easily identified because the boundaries of neighbourhoods are not clearly defined. Two approaches are possible to address the limitation, therefore worth further research.
The first approach is to develop a sharing algorithm that can identify the condition of convergence with a neighbourhood. Graph isomorphism and other information can be exploited. The alternative approach is to implement a parallel evolutionary algorithm (e.g. the Island model [Web01]) that has a number of isolated sub-populations evolved separately. At certain stages of evolution, the individuals in the sub-populations are allowed to migrate to other sub-populations. As randomly initialized searches are unlikely within the same neighbourhood, the parallel algorithm tends to search in multiple neighbourhoods at once. This has the same effect as the multiple trial optimisations in solving the example problems (Chapter 7 and 8). Also with migration, useful genetic information can be transferred between sub-populations; therefore provide a similar effect as seeding (Chapter 8, 8.4.2). The sharing approach and the sub-population approach can also be used together for the extra exploration power.
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Appendix A

Inventory of Existing HVAC Configurations

The secondary HVAC systems are the air-conditioning and distribution systems that have means to heat, cool, humidify, dehumidify, clean and distribute air to the various conditioned spaces in a zone. Secondary HVAC systems are generally categorised into All-Air systems, Air-Water systems, All-Water systems and Unitary systems. In All-Air systems, the energy is carried to the conditioned space solely by ducted air. In All-Water systems, the energy is carried to the conditioned space by piped liquid, usually water. In this case, the energy transfer occurs directly with the air in the occupied space. Air-Water systems, however, utilise a combination of air and water for transporting energy. Both fluids are distributed to each space to perform the cooling/heating function. Unitary systems are factory-matched primary and secondary components in single packages.

From the perspective of air-conditioning and distribution processes, the secondary HVAC systems can be described by physical realisation (single/dual/multi-duct); air flow control strategy (constant-variable-volume); and by strategies for handling multiple zones and the re-circulation of exhaust air. This Appendix illustrates some of the typical system configurations, and their representation by fundamental air-handling processes, as could be automatically synthesized by the optimisation process. The generic form of schematic diagram for each configuration is also illustrated.
A.1 Single Duct Systems

Single-duct systems convey either heated or cooled air by the same duct. Depending on whether the total volume of supplied air varies in concordance with the change of ambient condition and zone load, Single-duct systems can be further divided into Single-duct constant-volume systems and Single-duct variable-volume systems.

A.1.1 Constant Air Volume (CAV) Systems

While maintaining constant airflow in the main ducts, the single-duct constant-volume systems adjust the supply air condition in response to the space load. The simplest system is a supply unit (air handler) serving a single zone. The basic components of such a system are supply air fan, cooling coil, reheat coil, return air fan, and re-circulation of part of the return air. Settings of the dampers, fans, and the cooling coil are generally fixed for each season, while the reheat coil is controlled by a room thermostat to maintain the desired temperature in the zone. A preheat coil may be used in cold climates. Humidifiers may also be incorporated if the control of humidity is required. In multiple-zoned applications, the reheat coils must be installed and controlled for each zone. Another method of controlling supply air condition in a single-duct constant-volume system is the utilisation of a bypass box. The system diagrams of the varieties of single-duct constant-volume systems can be found in 1996 ASHRAE Handbook, page 2.5, Fig. 8 [ASH96].

Single Zone Systems

The representation of air-handling processes of the single-zoned single-duct constant-volume systems is shown as Figure A.1. Settings for the fans, the mixing box (proportion of fresh air to re-circulated return air), the output of the preheat coil, and cooling coil are decided on seasonal ambient conditions and space load. The operation of these components is kept constant after each seasonal setting. The reheat coil and the humidifier (if required) are controlled by the thermostat and humidistat respectively, each of which is located in the space.
Multiple Zoned with Reheat

The representation of air-handling processes of the multiple-zoned single-duct constant-volume systems with reheat is shown as Figure A.2. As for the single-zoned application, settings for the fans, mixing box, preheat and cooling coils are decided on seasonal ambient conditions and space load. Reheat coils are controlled by thermostats located in the corresponding spaces.
CAV with Terminal Bypass

The representation of air-handling processes of the multiple-zoned single-duct constant-volume systems with bypass, also known as variable volume and temperature systems (VVT), is shown in Figure A.3. The bypass box takes the place of reheat coil in the multiple-zoned single-duct CAV with reheat. The volume of air supplied to zone is controlled to maintain the desired zone condition. The bypassed air is discharged to the ceiling, where it is mixed with return air and drawn back to the return ducts. The ceiling, therefore, is functioning as a mixing box.

![Diagram of CAV with Bypass](image)

**Figure A.3 The configuration of the single-duct CAV system with a bypass terminal**

A.1.2 Variable Air Volume (VAV) Systems

A VAV system controls temperature within a space by varying the quantity of supply air rather than varying the supply air temperature. Varieties of configuration are based on the VAV terminal devices that are used at the zone to vary the quantity of supply air to the space. The diagram of single-duct VAV systems with reheat, fan-powered, and induction VAV terminal devices can be found in *1996 ASHRAE Handbook*, page 2.6, Fig. 9 [ASH96].

VAV with Terminal Reheat

The representation of air-handling processes of the single-duct variable air volume systems with reheat terminal is shown as Figure A.4. The reheat VAV terminal is composed of a damper and a reheat coil. Both of the volume and the temperature of the air supplied to
zone are controlled by thermostat located in the zone, to maintain the desired condition. The fans in the principal circuit; the heating and/or cooling of the air; and intake of outdoor air, are controlled to follow the air-conditioning load of the building.

![Diagram of single-duct VAV with reheat terminals](image)

**Figure A.4 The configuration of the single-duct VAV with reheat terminals**

**VAV Terminal Induction Box**

The representation of air-handling processes of the single-duct variable air volume systems with induction box is shown in Figure A.5. The induction box is composed of a mixing box, a reheat coil and a "virtual" fan. In the representation, the virtual fan mimics the induction effect produced in the real unit.

![Diagram of single-duct VAV system with induction terminals](image)

**Figure A.5 The configuration of the single-duct VAV system with induction terminals**
Fan Powered Terminal Units

The representation of air-handling processes of the single-duct variable air volume systems with fan-powered terminal box is shown as Figure A.6. The fan-powered box comprises a reheat coil and a fan that are both controlled by the space condition.

![Fan Powered Terminal Units Diagram](image)

Figure A.6 The configuration of the single-duct VAV system with fan-powered terminals

Dual Conduit System

The dual-conduit system (see 1996 ASHRAE Handbook, page 2.7, Fig. 10 [ASH96]) is designed to provide two air supply paths, one to offset exterior transmission cooling or heating loads, and the other where cooling is required throughout the year. The primary air stream operates as a constant volume system, and the air temperature is varied to offset transmission only. The secondary air stream is cool year-round and varies in volume to match the load.

The representation of dual conduit systems is shown in Figure A.7. The “primary system” in the Figure A.9 is described as a CAV with fan and reheat coil that re-circulate the return air to the zone. Practically, supply air from “primary” and “secondary” conduits is mixed in the zone. Therefore, a mixing box is synthesised to represent the process.
Variable Diffusers

System representation of VAV systems of the Variable diffusers type is similar to that of basic VAV boxes (Figure A.4) with/without reheat coils. The variable diffusers function as dampers that are adjustable according to zone conditions.

A.2 Dual-Duct Systems

Dual-duct systems condition all the air in a central apparatus and distribute it to the conditioned spaces through two parallel ducts, one duct carrying cold air and the other, warm air. The temperature in an individual space is controlled by mixing the warm and cool air in proper proportions. Different arrangement of terminals and operations leads to numerous varieties of dual-duct systems.

Dual-duct systems can be used for both single-zoned and multiple-zoned applications. The system diagrams are effectively same except the number of zones supplied. Operation manners such as constant air volume (CAV) and variable air volume (VAV) are both applicable.
A.2.1 Constant Air Volume (CAV) Systems

The system diagram of the dual-duct single-fan CAV system can be found in 1996 ASHRAE Handbook, page 2.7, Fig. 11 [ASH96]. Actions of the face and bypass damper are synchronised so that the proportion of warm air and cool air can be controlled while maintaining the constant air flow through the main duct. Representation of the dual-duct single-fan CAV system is shown in Figure A.8.

![Figure A.8 The dual-duct single-fan CAV system configuration](image)

A.2.2 Variable Air Volume (VAV) Systems

Dual-duct variable volume systems blend quantities of cold and warm air to achieve a desired air condition. Beside dual-duct VAV boxes, these systems may also include single-duct VAV terminals connected to the cold deck for cooling-only of interior spaces. Configurations are varied on arrangement and control of fans. The single-fan implementation uses fan control maintaining the static pressures on both decks (see 1996 ASHRAE Handbook, page 2.7, Fig. 12 [ASH96]); whereas the dual-fan arrangement uses one supply fan in each of the main ducts (1996 ASHRAE Handbook, page 2.8, Fig. 13 [ASH96]).

System configurations for the dual-duct VAV systems are shown in Figure A.9 and Figure A.10, respectively. The typical dual-duct VAV box is represented as a combination of dampers and a mixing box.
A.2.3 Other Multi-Zoned Systems

The Three-Deck, or Texas Multizone systems are similar to that in Figure A.8, except a terminal heating coil is used for each zone. See Figure A.11 for the representation.
It is also arranged as a three-duct system, in which a static pressure plate is used in parallel with heating coil and cooling coil. A set of three jointly operated dampers is fitted for each zone, and the air supplied to the zones is a mixture from the three paths. Configuration is shown in Figure A.12.

A.3 Air-Water Systems, All-Water Systems, and Unitary Systems

Primary air handling sub-systems in air-water systems and refrigerant-based systems are similar to single-duct CAV systems. Representation of the system varies according to arrangement of the air system and the water system.
For fan-coil systems and induction unit systems, where primary air and zone air are mixed before supplied to the space, the representation is as in Figure A.13:

![Diagram of fan-coil/induction unit systems](image)

**Figure A.13 The configuration of fan-coil/induction unit systems**

The representation of fan-coil systems, induction units and unitary systems that do not mix the zone air with fresh air, is same as panel heating and cooling systems. Room air conditioners with fresh air systems, where the mixing of fresh air and re-circulated air happens in the space, are similar also. Therefore, the scheme of the system can be effectively represented as Figure A.14.

![Diagram of Fan-Coil system with a dedicated fresh air system](image)

**Figure A.14 The configuration of the Fan-Coil system with a dedicated fresh air system**
A.4 Special Systems

The “special systems” included here are, primary/secondary systems, up air systems, wetted duct and super saturated systems, compressed air and water spray systems, and low temperature systems.

A.4.1 Primary/Secondary Systems

Primary/Secondary systems can be found in situations where space gains are very high, and a large number of air changes are required (see 1996 ASHRAE Handbook, page 2.8, Fig. 14 [ASH96]). The configuration of the primary/secondary systems is shown in Figure A.15.

![Figure A.15 The Primary/Secondary air system configuration](image)

A.4.2 Up Air Systems

Up Air Systems differ from other systems in the positioning of air supply. Terminals are mounted beneath the floor and suitable for providing individual control. System configuration is similar to single-/dual-duct VAVs.

A.4.3 Wetted Duct/Supersaturated Systems

Spraying water into the air stream at central air handling units in sufficient quantities provides super-cooled supply air. These systems are used where high humidity is desirable (See 1996 ASHRAE Handbook, page 2.8, Fig. 15 [ASH96]).
A.4.4 Compressed Air and Water Spray Systems

This system is similar to the wetted duct system, except that the water is atomised with compressed air.

A.4.5 Low-Temperature Systems

These systems supplies low temperature air to the zones, where special terminals must be fitted to maintain minimum airflow for comfort. See Figure A.16 for the representation of system and the re-circulation terminal.

![Diagram](image.png)

Figure A.16 The configuration of the low-temperature system