

Method of Operating a Building Environment Management System

Field of the Invention

[0001] The present invention relates to a method of operating a building environment management system (BEMS). Particularly, but not exclusively, the invention relates to the energy-efficient scheduling of a Heating, Ventilating and Air Conditioning (HVAC) system.

Background

[0002] The building sector represents more than 40% of worldwide primary energy consumption, 72% of US electricity consumption, and 38% of carbon dioxide (CO₂) emissions. In tropical Singapore, electricity comprises the single largest building operating expense with up to 60% of the energy consumed being used for air-conditioning. Much of this energy is wasted. Environmental Protection Agency studies suggest that energy savings of 30% can be realised through improvements to facilities and facility management, while more aggressive measures promise even greater savings.

[0003] A building is a complex, thermally interconnected dynamical system. Existing approaches for Heating, Ventilating and Air Conditioning (HVAC) management in commercial buildings fall into two broad categories. The first strategy is to use advanced control to ensure zone temperatures follow pre-specified set-point trajectories with possible fluctuations that fall within a comfort band, while minimising the energy consumption during this process. Many of these schemes use model predictive control (MPC) to handle complicated constrained multivariable problems that take into account uncertainty. The second strategy is to schedule HVAC operations based on optimised set-point profiles.

[0004] Many HVAC control methods are centralised, involve sophisticated optimal control methods, and aim to minimise the total energy consumption across all zones. As mentioned above, model predictive control is very widely used for its ability to handle complicated constrained multivariable problems combined with uncertainty. For example, Kelman and Borelli propose a MPC approach to minimise energy use and satisfy occupant constraints using a sequential quadratic programming algorithm (see reference 1 of the references listed at the end of the description). This technique

provides a locally optimal solution that reproduces some known scheduling strategies like pre-cooling, but the computational complexity is unfavorable when applied to large buildings.

[0005] The power drawn by a chiller in an HVAC system is approximately linear under a cooling load in the simplest model. The power drawn by HVAC fans is approximately cubic or quadratic in relation to a mass flow rate of air. Accordingly, large peaks in the total mass flow rate of air are undesirable as they result in greater energy consumption. Pre-cooling zones in advance of their occupancy offers an attractive strategy for energy efficiency gains. However, the pre-cooling strategy must be carefully tuned. Conservative pre-cooling strategies fail to flatten the mass flow rate of air sufficiently. Conversely, pre-cooling well in advance of what is required increases energy consumption because the cumulative cooling load is larger than necessary. In essence, pre-cooling serves to shift loads by exploiting demand temporal flexibility and a natural thermal mass in zones. The most effective pre-cooling strategies require accurate forecasts of occupancy, solar insolation, zone temperature set-points, and cooling load in each zone. This can involve expensive sensing infrastructure costs. Model-predictive control methods have been studied to optimise pre-cooling strategies but these techniques are sensitive to forecast accuracy. Currently, many commercial buildings use a “naïve” pre-cooling strategy. The cooling system in a workplace is generally switched on at a fixed time (say 1 hour) before the work day begins (e.g. at 9 am) and all zones are cooled to the same set-point, irrespective of their cooling load, and without regard to occupancy.

[0006] Other research on HVAC operational efficiency includes demand shifting, occupancy-based scheduling, set-point selection, base-lining, aggressive duty cycling, and scheduling that accounts for time-of-use electricity pricing.

[0007] However, existing scheduling techniques have four principal shortcomings which are:

- 1) limited scalability due to high computational complexity of scheduling algorithms,
- 2) suboptimal energy savings due to model approximations and lack of coordination between optimisation for air handling and chiller equipment,
- 3) prohibitive deployment costs due to the use of centralised architectures and user-calibrated models, and
- 4) inadequate integration with Indoor Environment Quality (IEQ) constraints which limit their acceptability.

[0008] It is therefore an aim of the present invention to provide a method of operating a building environment management system (BEMS) that helps to ameliorate one or more of the above shortcomings.

Summary of the invention

[0009] In accordance with a first aspect of the invention there is provided a method of operating a building environment management system (BEMS) comprising:

- a) obtaining zone environmental sensor data and zone set-points for two or more zones in a building;
- b) computing, for each zone, a request for a minimum cooling/heating air supply rate to meet the zone set-points;
- c) communicating the request for each zone to a scheduler;
- d) receiving, at the scheduler, the requests for each zone and energy efficiency data on one or more components of the BEMS;
- e) calculating an air supply strategy comprising a cooling/heating air supply allocation for each zone to minimise energy consumption of the one or more components, while aiming to satisfy all zone set-point requirements; and
- f) controlling the BEMS to deliver the allocation of step e) to each zone.

[0010] Thus, embodiments of present invention provide a novel, computationally efficient and scalable air distribution scheduling and control approach. The requests for a particular cooling/heating air supply rate can be considered to be requests for a particular number of tokens and the cooling/heating air supply allocation can be considered as a token allocation. This approach utilises an original hierarchical architecture, featuring locally (among individual zones) generated cooling/heating service (or token) requests together with centralised service/token allocations by the scheduler. It is believed that this strategy would realise aggressive targets for energy efficiency in BEMS such as HVAC systems (including variable air volume (VAV) systems), while respecting human comfort and air quality constraints. Notably, this solution enables rapid and cost-effective deployment both in new buildings and for retrofits. Furthermore, the method is adaptive to occupancy and environment changes and robust by supporting fault detection and isolation of individual zones.

[0011] The architecture proposed offers several key advantages over existing approaches. For example, the architecture is scalable to realistic buildings with more than 500 thermal zones as the computational burden both on individual zone modules and the scheduler is modest. Co-ordination of token requests for individual zones

ensures the best energy saving in the BEMS. Zone modules naturally deliver robustness as local models can be adaptively tuned to non-stationary environments, zone requests can accommodate abrupt changes in projected occupancy, and local environmental sensor data can serve to detect and localise faults. Indoor environmental quality (IEQ) constraints can be explicitly handled as constraints on return-to-fresh air ratios. Finally, the modular nature of the architecture implies that deployment costs will be minimal. Preliminary investigations (omitting IEQ constraints) reveal the promise of this approach as zone module computations reduce to linear programming, while the scheduler computations reduce to quadratic programming. Furthermore, in embodiments where a chiller/heater system is not directly accessed by the scheduler, but indirectly optimised through an air handling unit (AHU) by adjusting building cooling loads, inexpensive retrofits can be achieved.

[0012] The scheduler can be considered to be centralised in that it operates as a single entity to schedule air supply to each of the individual zones. In practice, the scheduler need not be located centrally within the BEMS or building.

[0013] The zone set-points may comprise pre-determined values or acceptable ranges for the environmental sensor data. These may be pre-programmed or determined by user input.

[0014] The one or more components of the BEMS may comprise an air handling unit. More specifically, the one or more components may comprise a fan and/or damper associated with the air handling unit. Additionally, or alternatively, the one or more components may comprise a chiller or heater.

[0015] The method may further comprise repeating steps a) to f) at pre-defined time-intervals and/or when the zone environmental sensor data reaches a pre-defined value.

[0016] The requests may convey an amount of cooling/heating required and an urgency of the request. For example, the request may convey the amount of cooling/heating required, by when and for how long.

[0017] The requests may be determined for multiple time periods (i.e. horizons). The multiple time periods may comprise periods with a common start time and different end times. Thus, the cooling/heating air supply rate required for the next 30 minutes, next hour, next 2 hours etc. may be calculated and communicated to the scheduler. In this way, the scheduler may take a long or short term view of the cooling/heating requirement to try to flatten out the effects of any peak demand periods on the energy efficiency of the BEMS.

[0018] The scheduler may be configured to take into account a chiller/heater coefficient of performance and/or air duct network design constraints when minimising energy consumption.

[0019] The zone set-points may be determined on the basis of thermostat settings or may be input to the system through a user interface.

[0020] In accordance with a second aspect of the invention there is provided a building environment management system (BEMS) comprising:

a) two or more zone modules configured to:

- i. obtain zone environmental sensor data and zone set-points;
- ii. compute a request for a minimum cooling/heating air supply rate to meet the zone set-points within each respective zone; and
- iii. communicate the request for each respective zone to a scheduler;

and

b) a scheduler configured to:

- i. receive the requests for each zone and energy efficiency data on one or more components of the BEMS;
- ii. calculate an air supply strategy comprising a cooling/heating air supply allocation for each zone to minimise energy consumption of the one or more components, while satisfying all zone set-point requirements; and
- iii. control the BEMS to deliver the allocation of step ii) to each zone.

[0021] The BEMS may further comprise zone sensors for obtaining the environmental sensor data which may comprise one or more of temperature, air pressure, carbon dioxide (CO₂) concentration, humidity, occupancy and condition or status of windows and/or doors (e.g. open or closed).

[0022] The BEMS may comprise a communication network infrastructure for communication between each zone module and the scheduler. The network may be wired but is preferably wireless for ease of installation.

[0023] In some embodiments, the BEMS may be configured to adjust damper or fan settings to regulate a flow of cool/warm air to the zones.

[0024] Each zone module may comprise one or more local mathematical models configured for predicting environmental (e.g. thermal) conditions within the respective zone. The local models may include forecasts of weather, cooling/heating load, zone set-points and occupancy.

[0025] A goal of the present scheduling approach is to minimise energy consumption for the BEMS, for example, through more efficient operation of the air handling unit

AHU (which may comprise one or more fans and/or dampers) and/or the chiller/heater system, while providing for a user-specified zone comfort level. In general, there are two stages of decision-making as described below for a particular embodiment.

[0026] Stage 1 (relating to the request generation) takes place in each individual zone, which may be a room or an area within a room. A zone module (ZM) takes zone environmental sensor data and zone set-points (such as temperature, humidity and a fresh air/returned air ratio) determined by a (given) human input or comfort model or an Indoor Environment Quality model, and computes a request for the minimum cooling/heating air supply rate (e.g. in term of the number of tokens) that may meet the zone set-points, while having a potential of minimising the BEMS energy consumption. During this process, a complex thermal dynamics model in the form of a local model for each zone, an ideal BEMS energy consumption model and a zone human comfort model may be considered in order to ensure that the minimum cooling/heating air supply rate requested is properly chosen, which can save energy for the BEMS while ensuring zone comfort.

[0027] Stage 2 (relating to the air supply rate allocation) takes place in a centralised scheduler (CS). The CS takes all zone requests (i.e. the requested amount of cooling/heating air supply rate from each zone, as opposed to the amount of cooling/heating air itself), and its knowledge on actual BEMS component (e.g. air handling unit or chiller/heater) power efficiencies into account, and calculates a cooling/heating air supply strategy (i.e. token allocation) for each individual zone, which would lead to minimum energy consumption of the BEMS, while satisfying all zone set-point requirements.

[0028] This two-stage decision-making procedure can solve an HVAC energy optimisation problem in a distributed and hierarchical manner. This HVAC energy optimisation problem addresses the energy consumption of the in-building part of an HVAC system in a more computationally efficient manner than the prior art (e.g. example embodiments of the invention can handle more than 200 zones, while a conventional method can handle no more than 50 zones in low-level optimisation) due to the proposed two-stage, distributed, hierarchical, decision-making (or optimisation) procedure. The two-stage decision-making procedure induces a simple hierarchical information architecture, which may be quickly deployed in a new or old building with an extremely low deployment cost. This simple hierarchical information architecture may render high flexibility, adaptability and robustness for an actual deployment.

[0029] Example embodiments of the invention address an optimal HVAC scheduling/control problem instead of merely a communication problem in a conventional method and focus on a novel scheduling/control strategy with the simple hierarchical information architecture described above, allowing a quick deployment. The simple hierarchical information architecture proposed in example embodiments of the invention is not limited to use of a wireless communication network, but may comprise an integration of any suitable, cost-effective communication network and local/centralised decision modules for energy efficiency optimisation.

[0030] In embodiments of the invention, the cooling/heating requirement of a zone can be regarded as a service. The provider of the service is the BEMS (which may be implemented by a HVAC system) and the customers are the different thermal zones in the building. The central concept can be considered to be that of tokens. These represent requests for cooling/heating service in various time windows. The tokens may be expressed in terms of a desired mass flow rate of cool/warm air that a zone might need in order to meet temperature constraints determined by occupants through thermostat settings. The requested tokens may be provided by an air handling unit (AHU) by adjusting damper or fan settings that regulate a flow of cool/warm air to the zones.

[0031] Each zone may be associated with a zone module, which maintains a local model for heat transfer within the zone, processes available measurements from local sensors (i.e. zone environmental sensor data), and responds to user-specified temperature requests (i.e. set-points). Specifically, the zone module may conduct the following operations in sequence:

- ZM1. Information processing of forecasts of weather, cooling/heating load, zone set-points, and occupancy
- ZM2. Forecast zone cooling/heating loads in future time periods
- ZM3. Compute (token) requests for cooling/heating service in future time periods
- ZM4. Update local models in the zone module

[0032] Notably, all zone module computations are decentralised. In principle, the token requests from various zones may be competing, may overload the capacity of the BEMS, or may result in energy inefficient operation of the BEMS. Thus, the centralised scheduler balances the requests and allocates tokens to each zone for the next time period. Specifically, the centralised scheduler may conduct the following operations in sequence:

- CS1. Gather (token) requests from all Zone Modules

CS2. Interrogate system state: IEQ, chiller/heater efficiencies, AHU status (e.g. damper positions, fan speeds), duct pressures, etc.

CS3. Compute operational constraints to meet requirements on air quality, minimum pressure etc.

CS4. Allocate tokens to each zone to minimise energy use subject to operational constraints

CS5. Issue control commands to the chiller/heater and/or the AHU (e.g. dampers and fans) to provide the allocated tokens to each zone

[0033] The allocation of tokens by the Centralised Scheduler attempts to minimise total energy use across the BEMS (e.g. including the chiller/heater and AHU which may comprise fans, dampers and pumps).

[0034] To explicitly respect IEQ and occupant comfort constraints inexpensive CO₂ sensors may be employed as a surrogate monitor for environment comfort, together with IEQ models. Combining sensors and models allows computation of IEQ constraints on return-to-fresh air ratios for each AHU (e.g. in step CS3). Chiller/heater coefficient-of-performance factors may be used from look-up tables to update energy cost functions. These may drive the token allocation optimisation of the Centralised Scheduler (e.g. in step CS4). Token allocation may be realised by issuing control commands to BEMS components such as the dampers, fans, chillers/heaters in the BEMS (e.g. in step CS5).

[0035] Computation conducted by the Centralised Scheduler may be centralised. Furthermore, the BEMS may implement a model predictive control (MPC) framework to mitigate modeling errors (e.g. in the energy consumption models), uncertainties (e.g. in forecasted cooling loads), and abrupt changes (e.g. due to faults or unexpected changes in occupancy). After each time period, the Zone Modules may have access to an effect of a control action on local variables (e.g. temperature) as obtained from the sensors in each zone. This information (e.g. the zone environmental sensor data) may therefore be used to update local models based on a measured thermal response from allocated tokens (e.g. in step ZM4). Future token requests may then be re-computed for subsequent time periods in a MPC framework (e.g. in steps ZM1, ZM2, ZM3).

Brief description of the drawings

[0036] Embodiments of the invention will now be described, by way of example only, with reference to the following drawings, in which:

- [0037] Figure 1A is a flow diagram illustrating a method of operating a building environment management system (BEMS) in accordance with an embodiment of the present invention;
- [0038] Figure 1B is a schematic diagram of a building environment management system (BEMS) in accordance with another embodiment of the invention;
- [0039] Figure 2 is a block diagram of a BEMS in accordance with an embodiment of the invention;
- [0040] Figure 3A is a graph of cooling load against time for daily use of a chiller in a BEMS;
- [0041] Figure 3B is a graph of ambient temperature against time;
- [0042] Figure 3C is a graph of returned air ratio against time;
- [0043] Figure 4A is a graph of simulated zone temperature over time;
- [0044] Figure 4B is a graph of cool air mass flow rate for different zones over time;
- [0045] Figure 4C is a graph of cool air mass flow rate for a fan of a BEMS over time;
- [0046] Figure 4D is a graph of power consumption over time;
- [0047] Figure 5 is a graph of energy against time;
- [0048] Figure 6A is a graph of zone temperature over time;
- [0049] Figure 6B is a graph of cool air mass flow rate for different zones over time;
- [0050] Figure 6C is a graph of cool air mass flow rate for a fan of a BEMS over time;
- [0051] Figure 6D is a graph of power consumption over time;
- [0052] Figure 7A is a graph of zone temperature over time;
- [0053] Figure 7B is a graph of cool air mass flow rate for a fan of a BEMS over time;
- [0054] Figure 7C is a graph of power consumption over time;
- [0055] Figure 8 is a schematic diagram of a building environment management system (BEMS) in accordance with another embodiment of the invention;
- [0056] Figure 9 is a pneumatic diagram showing air supply from a fan to different zones in the BEMS of Figure 8;
- [0057] Figure 10 is a graph of supply fan efficiency against percentage load;
- [0058] Figure 11A is a graph of simulated zone temperature over time;
- [0059] Figure 11B is a graph of cool air mass flow rate for different zones over time;
- and
- [0060] Figure 11C is a graph of power consumption over time.

Detailed description

[0061] In accordance with an embodiment of the present invention there is provided a method 500 of operating a building environment management system (BEMS) as illustrated in Figure 1A. The method 500 comprises the following steps:

Step 502: obtain zone environmental sensor data and zone set-points for two or more zones in a building;

Step 504: compute, for each zone, a (token) request for a minimum cooling/heating air supply rate to meet the zone set-points;

Step 506: communicate the request for each zone to a scheduler;

Step 508: receive, at the scheduler, the requests for each zone and energy efficiency data on one or more components of the BEMS;

Step 510: calculate an air supply strategy comprising a (token) cooling/heating air supply allocation for each zone to minimise energy consumption of the one or more components, while aiming to satisfy all zone set-point requirements; and

Step 512: control the BEMS to deliver the allocation of step 510 to each zone.

Example 1

[0062] In accordance with a specific embodiment of the present invention there is provided a building environment management system (BEMS) 10 as illustrated in Figure 1B, that is configured to carry out the method of Figure 1A. More specifically, the BEMS 10 is configured as a heating, ventilating and air-conditioning (HVAC) system that utilises a token-based approach for air distribution scheduling for efficient operation. Notably, in this embodiment coefficients of performance for components of the BEMS 10 are not considered.

[0063] Figure 1B shows information flow within an architecture of the HVAC system. The architecture comprises individual zone modules 12, a centralised scheduler 14 and a communication network 16. The zone modules 12 each comprise a processor 18 and sensors 20. Advantageously, the centralised scheduler 14 may be configured to control an existing HVAC system comprising a chiller or heater by providing appropriate input signals to an existing air handling unit (AHU) 22. The AHU 22 is configured to operate one or more supply fans 24 and/or dampers 26 to control an air mass flow rate into each zone in order to control the environmental conditions therein. One striking feature of this architecture is that an existing chiller/heater control system can be left intact. This is possible because the centralised scheduler 14 does not directly control a chiller/heater subsystem, but rather, indirectly minimises operational energy use in the building by regulating a cooling/heating load seen by the

chiller/heater (which is implemented by control of the AHU 22). Importantly, this feature negates the need for costly interfacing with proprietary chiller/heater subsystems, detailed domain knowledge, and particular details of an installation base for the HVAC system.

[0064] As mentioned above, cooling or heating requirement may be regarded as a service provided by an HVAC system where customers are constituted by individual zones in a building or home. In particular, the service may be delivered by a mass flow rate of cool/warm air, which may be measured in tokens.

[0065] In the present embodiment, the zone modules 12 are configured to compute service (i.e. token) requests on the basis of zone environmental sensor data (e.g. temperature, humidity, insolation, occupancy) and zone set-points, which may comprise a user-defined comfort range. More specifically, the zone module 12 comprises a local (mathematical) model of the environment which takes as inputs, the zone environmental sensor data sensed by the sensors 20 and produces, as an output, a minimum cooling/heating air supply rate (in the form of a token request) to meet future zone set-points. The token request is sent via the communication network 16 (e.g. a wired or wireless internet protocol IP connection) to the centralised scheduler 14. Notably, the zone modules 12 and token requests are decentralised and this allows fast linear computation of a forecasted cooling/heating service requirement over pre-defined timescales.

[0066] The centralised scheduler 14 receives the token requests from two or more zone modules 12 over the communication network 16 and responds by allocating tokens (i.e. controlling an air supply rate through the HVAC system) to deliver a required heating/cooling service in each zone via a token allocation provided to each zone. In the present embodiment, the centralised scheduler 14 uses model predictive control (MPC) to balance the token requests from each zone against an energy cost for operation of the HVAC system. The allocated tokens are used by the centralised scheduler 14 to control the HVAC system (i.e. the AHU 22) to provide the required air supply rate in each zone. In particular embodiments, this may comprise flattening an AHU's supply fan mass flow rate profile to minimise energy consumption. Importantly, the centralised scheduler 14 can employ fast quadratic computations.

[0067] In operation, the air supply rate provided to each zone changes the environmental conditions in the zone which in turn affects the zone environmental sensor data sensed by the zone module 12 and therefore the inputs to the local model change and a new output is computed in the form of a revised token request which is

sent to the centralised scheduler 14 for processing as described above. In this way, each zone module 12 serves to maintain and update its local model through a feedback process. It should be understood that the updating of the local model may be carried out at pre-set time intervals or when a certain threshold is reached (e.g. when the zone environmental sensor data changes by a pre-defined amount).

[0068] As mentioned above, this embodiment of the invention does not require direct modification of the chiller/heater control system. Instead, the HVAC system calculates optimal demand signals for control of the AHU's supply fan 24 and optimal damper 26 positions for each zone.

[0069] Advantages of embodiments such as those described above are that the HVAC system is easily scalable (e.g. it may take only 3-5 minutes for the HVAC system to deliver the token allocations to 150 or more zones), that there is low deployment cost, robustness to faults, enablement of fault detection and isolation (FDI), informed chiller staging and negligible energy performance loss when compared to a known non-linear optimisation strategy as will be explained in more detail below. Embodiments of the invention may therefore be particularly, but not exclusively, suitable for use in commercial buildings.

[0070] It will be understood that the zone modules 12 use local models and sensor 20 measurements to compute requests for HVAC service over various future time windows. As explained above, these requests are expressed in terms of the heating/cooling service required which may be conceptually regarded as tokens. The centralised scheduler 14 balances the token requests from the zone modules 12 and allocates tokens to each zone for a subsequent time-slot. This allocation attempts to minimise total energy consumption in the HVAC system, while respecting operational constraints. The zone modules 12 update their local models based on measured thermal responses resulting from the allocated tokens, and re-compute future token requests.

[0071] Algorithms of the zone modules 12 for computing token requests and the centralised scheduler 14 for allocating tokens have been developed and simulated to demonstrate that a performance loss of the present token-based approach is modest in comparison to a fully centralised nonlinear optimisation approach as described below.

Variable Air Volume (VAV) Air-conditioning System

[0072] In the present embodiment, the BEMS is an HVAC system that is constituted by a Variable Air Volume (VAV) air-conditioning system 30 as shown in Figure 2. Whilst

such a VAV system is primarily concerned with chilling air to a comfortable temperature in a hot climate, it will be understood that the principles of the present embodiment may also be applied to other HVAC systems and BEMS, for example, those that concern heating as opposed to chilling.

[0073] A zone 34 may be regarded as an area inside a building that is controlled by a single thermostat. It could be a part of a large room or might comprise several small rooms. The VAV system 30 in Figure 2 has a duct 32 servicing multiple of such zones 34 numbered 1, 2...n. The VAV system 30 includes a chiller 36 that comprises units of various capacities that produce chilled water 38 at a fixed temperature (typically 4-7°C) and with a fixed flow rate. These units are staged based on typical daily cooling load patterns that the building experiences. The VAV system 30 further comprises a VAV Air Handling Unit 40 (VAV AHU) that receives chilled water 38 from the chiller 36 and fresh outside air 44 filtered through external duct 42. This means that air supplied to the VAV AHU 40 is a mix of the fresh outside air 44 plus re-circulated air 46. The fresh outside air 44 is used to keep CO₂ levels within mandated levels, and re-circulated air 46 is used because it has lower humidity and is already cooled. A heat exchanger comprising cooling coils (not shown) uses the chilled water 38 to cool the air supplied to the VAV AHU 40 to a pre-set temperature set-point (typically 12-14°C). The VAV AHU's cool air output 48 is then forced by a supply fan 50 into the duct 32 in the building. The supply fan 50 is responsible for creating sufficient pressure differences to ensure that the cool air output 48 is available at all zones 34 requesting a cooling service.

[0074] As can be appreciated from the above, the VAV AHU's cool air output 48 is used to cool the various zones 34. Accordingly, a portion of the cool air output 48 mixes with existing warmer air to cool each zone 34, and flows back to the VAV AHU 40 through the duct 32. Mass flow rate of supplied cool air to each zone 34 is controlled by dampers 52 that can alter the cross-sectional area of the duct 32 opening to each one of the zones 34. The VAV system 30 may also comprise a control module (not shown) that receives information from thermostats fitted in each zone 34 and controls the dampers 52 to meet user-specified zone temperature set-points.

[0075] An aim of embodiments of the present invention is in minimising the overall operational energy consumption in the HVAC system through improved scheduling and/or control. The components with the most significant energy consumption are the chiller 36 and the supply fan 50 in the VAV AHU 40. Of these, the chiller 36 consumes over 75% of the total energy used although efficiency gains could be realised through

optimised chiller staging. Energy consumption in other HVAC system components (e.g. pumps) is less significant, and being relatively fixed, offers modest potential for efficiency gains through improved control.

Component Models

[0076] Embodiments of the invention will now be described in relation to equations and component models employed by the zone modules 12 and the centralised scheduler 14. It should be noted that the equations and component models described herein could be employed in any of the architectures illustrated in the figures. However, for ease of illustration, the embodiment of Figure 2 will be referred to in the description below, as an example.

[0077] In Figure 2, the chiller 36 constitutes a single centralised chiller that serves the single VAV AHU 40 responsible for providing cool air to all zones 34. In this embodiment, a coefficient of performance of the chiller 36 is assumed to be constant across operating points and an air duct pressure distribution associated with allocated cool air mass flow rates is not considered in order to simplify the description of the present embodiment. In Example 2, described below, these assumptions are removed to illustrate a more general embodiment of the invention. In both examples, humidity effects are not considered, for simplicity of illustration. Furthermore, it is assumed that air mixing within any zone 34 is instantaneous.

[0078] The following nomenclature is used throughout.

δ	Sampling time
$\dot{m}_i$	Mass flow rate of cool air supplied to zone i
$\dot{m}_{ih}$	Upper bound of mass flow rate of cool air for zone i
$\dot{m}_{il}$	Lower bound of mass flow rate of cool air for zone i
$\dot{m}_{SA}$	Mass flow rate of supply air at the VAV AHU 40
$\dot{Q}_i$	Cooling load in zone i
η_f	Supply fan 50 efficiency
μ_c	Coefficient of performance of the chiller 36
ρ	Fluid density
c_i	Thermal capacitance of zone i
c_p	Specific heat capacity of air
d_r	Return air to mixed air ratio
g_i	Cooling energy supplied to zone i

H_p	Prediction horizon
i	Zone 34 index
k_f	Supply fan 50 power function coefficient
n_z	Number of zones 34
p	Pressure
P_c	Power consumption of the chiller 36
P_f	Power consumption of the supply fan 50
R_i	Heat transfer coefficient for zone i
T_c	Temperature of cool air
T_i	Temperature of zone i
T_{ih}	Upper bound of comfortable temperature range for zone i
T_{il}	Lower bound of comfortable temperature range for zone i
T_{oa}	Temperature of fresh outside air 44

Zone Module Local Model

[0079] Optimal control/scheduling of the VAV system 30 requires a model to capture the thermal dynamics of the zones 34 and their interactions within a structure of the building. Many papers describe lumped electric circuit equivalent models for thermal zones. Others develop detailed prediction models that account for a wide variety of factors including physical building parameters, lighting, occupants and climate.

[0080] In the present embodiment, a simple bilinear thermal model illustrated in Equation (1) is employed as the local model. Equation (1) uses a known profile of cooling load Q to represent a load due to thermal input from internal loads and occupants, as well as coupling with adjacent zones and a constant R_i that represents thermal input from the environment.

$$c_i \dot{T}_i = \dot{m}_i c_p (T_c - T_i) + R_i (T_{oa} - T_i) + \dot{Q}_i \quad (1)$$

[0081] This local model decouples thermal dynamics across zones 34 because coupling effects are lumped into a disturbance process $\dot{Q}_i$. Note that this local model is nonlinear so as to capture mixing dynamics which appears as the product of a control input mass flow rate of cool air supplied to zone i , $\dot{m}_i$ and the temperature of zone i , T_i . This local model is discretised with sampling time δ as shown in Equation (2):

$$T_i(k+1) + \alpha_1 T_i(k) + \alpha_2 \dot{m}_i(k)(T_i(k) - T_c) = v_i(k) \quad (2)$$

where $\alpha_1 = \frac{\delta R_i}{c_i} - 1$, $\alpha_2 = \frac{\delta c_p}{c_i}$, $v_i(k) = \frac{\delta}{c_i} (\dot{Q}_i(k) + R_i T_{oa}(k))$, k is the sample index, and i is the zone index with $i = 1, \dots, n_z$.

[0082] An acceptable temperature range (i.e. zone set-point) for each zone 34 during occupied and unoccupied hours is specified in advance as:

$$T_{il}(k) \leq T_i(k) \leq T_{ih}(k) \quad (3)$$

[0083] In addition, the local model has access to forecasts of ambient temperature T_{oa} and cooling load profiles $\dot{Q}_i$, which are used to predict a random process $v_i(k)$.

[0084] In the present embodiment, a model-predictive control strategy is employed, as explained in more detail below, to deal with both increasing forward uncertainty in the above forecasts, as well as abrupt changes in the acceptable temperature range (possibly from occupancy forecasts or zone environmental sensor data).

Chiller

[0085] The chiller 36 is the principal component responsible for the cooling of the zones 34 in the building. In current practice, multiple chillers 36 coordinate to work at their best operating conditions to improve overall efficiency of the VAV system 30.

[0086] The function of the chiller 36 is to provide a continuous supply of chilled water 38 to cooling coils inside the VAV AHU 40. Warmer air passes over the cooling coils inside the VAV AHU 40 producing the cool air output 48 that serves to cool the zones 34. Models of the chiller 36 performance are complex and depend on the particular technology used. Calibrated performance curves supplied by a manufacturer of the chiller 36 specify the chiller 36 energy efficiency at various operating points. A detailed chiller 36 model based on first-principle heat transfer mechanisms with coefficients calibrated from the manufacturers' performance curves has been described in the prior art. However, such a detailed chiller 36 model is complex and has seen limited use in practical control applications. In another commonly used model, power consumption by the chiller 36 is quadratic in relation to a cooling load. In the present embodiment, a simple control-oriented chiller 36 model is used as described in Equation (4):

$$P_c = k_1(1 - d_r) \sum_{i=1}^{n_z} \dot{m}_i + k_2 d_r \sum_{i=1}^{n_z} \dot{m}_i (T_i - T_c) \quad (4)$$

where $k_1 = k_2(T_{oa} - T_c)$ and $k_2 = c_p/\mu_c$ and d_r is the return air to mixed air ratio. Note that the power consumption of the chiller 36 is not linear in relation to the mass flow rate of cool air $\dot{m}_i$, as the zone temperature T_i also depends on $\dot{m}_i$ through the local model used in the zone module 12 as per Equation (1).

Supply Fan

[0087] The power consumed by the supply fan 50 (which may be an axial or a centrifugal fan) depends principally on the mass flow rate of cool air and a pressure difference between an inlet and an outlet of the supply fan 50 as illustrated in the equation below.

$$P_f = \left(\sum_{i=1}^{n_z} \dot{m}_i \right) \frac{\Delta p}{\rho \eta_f}$$

As is known in the prior art, $\Delta p \propto (\sum_{i=1}^{n_z} \dot{m}_i)^2$. However, the pressure difference is approximately linear in the total mass flow rate of cool air. As a result, a quadratic supply fan 50 power model is commonly used as per Equation (5):

$$P_f = k_f (\sum_{i=1}^{n_z} \dot{m}_i)^2 \quad (5)$$

[0088] The mass flow rate of cool air to each zone 34 is constrained as per Equation (6) corresponding to minimum and maximum aperture sizes of the dampers 52.

$$\dot{m}_{il} \leq \dot{m}_i(k) \leq \dot{m}_{ih} \quad (6)$$

The General Scheduling Problem

[0089] Using the models above, it is possible to formulate a general scheduling problem in which the decision variables are the mass flow rates of cool air in each zone 34 $\dot{m}_i(k)$. An objective is to minimise the total energy consumption over the window $k = 1, \dots, W$ as expressed below:

$$\min \sum_{k=1}^{H_p} P_f(k) + P_c(k) \quad (7)$$

subject to the zone 34 thermal dynamics of Equation (2), constraints on the acceptable temperature ranges as per Equation (3), and limits on the mass flow rates of cool air in Equation (6).

[0090] This is a difficult optimisation problem because the thermal dynamics, constraints, and objective function are nonlinear in the decision variables $\dot{m}_i(k)$. In the prior art, sequential quadratic programming methods have been used to compute approximate solutions to this problem using a centralised nonlinear optimisation approach. Simulations have revealed that this (and other solution methods) are time-consuming even for a modest number of zones (< 50), and may fail to converge for realistic problems (e.g. with > 130 zones). In relation to the present embodiments, such

a centralised nonlinear optimisation approach is regarded as a benchmark, i.e. an “optimal” energy minimising strategy that can be used to assess the sub-optimality of the present embodiments of the invention.

The Architecture

[0091] As explained previously in relation to Figure 1B, the zone modules 12 in each zone 34 maintain local models regarding heat transfer, process user-specified temperature requests (i.e. zone set-points), and process available sensor 20 measurements in the form of zone environmental sensor data. The zone modules 12 receive forecasts of weather, cooling load, and occupancy. This information, together with the local models described above, is used to compute requests for cooling service over various future time periods. These requests are expressed in terms of the desired mass flow rate of cool air which is conceptually regarded as a token request. In relation to Figure 2, the tokens are provided by the VAV AHU 40 by adjusting settings for the dampers 52 to regulate the mass flow rate of cool air to the zones 34. The centralised scheduler 14 has the job of balancing the requests and allocating tokens to each zone 34 for the next time-slot in a manner that attempts to minimise total energy use while respecting operational constraints. As demonstrated below, an algorithm for token allocation can be reduced to quadratic programming.

Computing Token Requests and Token Allocation

[0092] The local model of Equation (2) for zone i is a bilinear dynamic model as the input $\dot{m}_i$ multiplies the state T_i . Forecasts of an exogenous noise process $v_i(k)$ on forward time windows are used and a critical transformation of the input variables is introduced as per Equation (8).

$$g_i(k) = \dot{m}_i(k)(T_i(k) - T_c) \quad (8)$$

[0093] These new decision variables $g_i(k)$ have an interpretation of cooling energy supplied to zone i in the k^{th} sample period. With this substitution, the thermal dynamics become linear as per Equation (9):

$$T_i(k+1) + \alpha_1 T_i(k) + \alpha_2 g_i(k) = v_i(k) \quad (9)$$

[0094] Regarding $g_i(k)$ as the new decision variables, the constraints on the acceptable temperature ranges in Equation (3) become linear inequalities. The objective function remains nonlinear (and non-convex). The dominant term in the

objective function is the cooling energy, and when the return air to mixed air ratio $d_r \approx 1$, this leads to:

$$P_c(k) = k_1(1 - d_r) \sum_i \dot{m}_i + k_2 d_r \sum_i \dot{m}_i (T_i - T_c) \\ \approx k_2 d_r \sum_i g_i(k)$$

which is linear in the decision variables $g_i(k)$.

Zone Module: Token Requests

[0095] Each zone 34 calculates its cooling energy requirements individually. These are computed over several future time horizons (or window) to obtain a cooling energy profile for each zone 34. For a fixed planning horizon H_p , for each zone i , an associated zone module 12 solves Equation (10) subject to Equations (11), (12) and (13):

$$J_i(H_p) = \min \sum_{k=1}^{H_p} d_r(k) g_i(k) \quad (10)$$

$$T_i(k+1) + \alpha_1 T_i(k) + \alpha_2 g_i(k) = v_i(k) \quad (11)$$

$$T_{il}(k) \leq T_i(k) \leq T_{ih}(k) \quad (12)$$

$$\dot{m}_{il}(k)(T_i(k) - T_c) \leq g_i(k) \leq \dot{m}_{ih}(k)(T_i(k) - T_c) \quad (13)$$

[0096] Note that $T_i(k)$ is a linear function of the decision variables $g_i(s)$; $s \leq k$ because the dynamics in Equation (11) are linear. This results in a linear programming problem which can be solved very quickly, and in parallel, in each zone 34.

[0097] It is possible to interpret $J_i(H_p)$ as a minimum cooling energy or minimum number of tokens needed by zone i on the planning horizon H_p to meet local temperature constraints. For a single planning horizon, $J_i(H_p)$ does not convey an urgency of the token request. To capture this, the zone module 12 solves the local model for various planning horizons $H_p = 1, 2, \dots, W$. Note that $J_i(H_p)$ is monotone increasing in H_p such that $J_i(1)$ is the minimum number of tokens needed in the first sample period, $J_i(2)$ in the first two periods, and so on. Thus the token request profile $J_i(H_p)$ of computed requests captures the urgency of the cooling requirements for zone i .

Conversion to Mass Flow Rate Constraints

[0098] To coordinate with the centralised scheduler 14, the zone modules 12 translate token requests into mass flow rate of cool air requests. More precisely, for a

fixed planning horizon H_p , $g_i^{opt}(k)$ is the optimal cooling request that solves Equation (10). Using Equation (11), it is possible to compute an associated optimal temperature profile $T_i^{opt}(k)$. Using Equation (8), it is possible to translate the token request into a mass flow rate of cool air request as below:

$$\dot{m}_i^{opt}(k) = \frac{g_i^{opt}(k)}{(T_i^{opt}(k) - T_c)}, k = 1, \dots, H_p$$

and a corresponding minimum total mass flow rate of cool air profile over each planning horizon required for zone i is computed as:

$$S_i(H_\omega) = \sum_{k=1}^{H_\omega} \dot{m}_i^{opt}(k), H_\omega = 1, \dots, W$$

[0099] In the present embodiment, this minimum mass flow rate of cool air profile $S_i(H_\omega)$ is transmitted to the centralised scheduler 14 using standard IP protocols over the communication network 16. The minimum mass flow rate of cool air profile (also referred to as a request profile) supplies a lower bound on the total mass flow rate of cool air demanded by zone i on the planning horizon H_p , as dictated by the local model for the zone 34 and acceptable temperature ranges (i.e. zone set-points).

Centralised Scheduler: Token Allocation

[00100] The centralised scheduler 14 attempts to allocate the mass flow rate of cool air requested by each zone 34 while minimising total energy consumption in the VAV system 30. In this step, the thermal dynamics in each zone 34 and acceptable temperature ranges for each zone 34 are discarded, as they are captured by the request profile $S_i(H_\omega)$. The centralised scheduler 14 therefore solves Equation (14) subject to Equations (15) and (16).

$$\min \sum_{k=1}^W \left(\frac{c_p}{\mu_c} \right) (1 - d_r(k)) (T_{oa}(k) - T_c) \sum_i \dot{m}_i(k) + P_f(k) \quad (14)$$

$$\sum_{k=1}^{H_\omega} \dot{m}_i(k) \geq S_i(H_\omega), H_\omega = 1, \dots, W, 1 \leq i \leq n_z \quad (15)$$

$$\dot{m}_{il} \leq \dot{m}_i(k) \leq \dot{m}_{ih}, 1 \leq i \leq n_z, 1 \leq k \leq W \quad (16)$$

[00101] The decision variables in this step are the mass flow rates of cool air $\dot{m}_i(k)$. The objective function is quadratic in the decision variables, and the constraints are linear inequalities. This is therefore a quadratic problem that can be efficiently solved with standard software tools. In essence, the centralised scheduler 14 tries to low-pass filter the request profiles for each zone 34 to reduce operational energy consumption.

Simulation Studies

[00102] Simulations were conducted for a synthetic building with five zones 34. The VAV system 30 comprised a single VAV AHU 40 servicing all five zones, and one centralised chiller 36 supplying chilled water 38 to cooling coils in the VAV AHU 40. The simulated architecture was essentially as illustrated in Figure 2 and as described above. The zone 34 service hours and desired zone (temperature) set-points employed are detailed in Table 1.

Zone	Occupied Hours		Acceptable temperature Range (°C)			
	start	end	Occupied Hours		Unoccupied Hours	
			Low	High	Low	High
1	7:00	19:00	21	24	12	32
2	6:00	18:00	21	25	12	32
3	9:00	13:00	20	22	12	32
4	5:00	19:30	21	23	12	32
5	5:00	19:30	21	24	12	32

Table 1: Zone Set-points

[00103] The thermal parameters used for the simulations are listed in Table 2.

Parameter	Value	Unit
c_p	1	kJ/(kgK)
c_i	1000	kJ/K
μ_c	4	dimensionless
R_i	0.15	kW/K
k_f	1.675	kWs ² /kg ²
T_c	12	°C
δ	30	minutes
H_p	24	hours
W	2	dimensionless
n_j	7	dimensionless
p_z	800	Pascal

Table 2: Thermal parameters

[00104] A desired cooling load profile and an ambient temperature profile employed is as shown in Figures 3A and 3B, and these were identical for all zones 34. The return air to mixed air ratio d_r that was used is also shown in Figure 3C.

[00105] The simulation results obtained using the equations described above are shown in Figures 4A, B, C and D. In particular, Figure 4A shows temperature profiles for each zone 34 and these reveal that the acceptable temperature ranges are respected for all zones 34 in the time periods concerned. The temperature profiles tend to follow the upper bound of the acceptable temperature ranges to expend minimal energy for cooling the zones 34. Figure 4B shows the mass flow rate of cool air for each zone 34 and Figure 4C shows the mass flow rate of cool air at the supply fan 50. Figure 4D shows the power consumption for the entire VAV system 30, P , compared with the power consumption for the chiller 36, P_c , and the power consumption for the supply fan 50, P_f .

[00106] The zones 34 in this embodiment are typically pre-cooled 60 minutes in advance of occupancy. Longer pre-cooling requires larger energy consumption in the chiller 36 because of increased net external cooling load, while shorter pre-cooling times result in larger mass flow rates of cool air increasing the energy consumption in the supply fan 50. The present embodiment balances these effects to minimise overall energy consumption.

[00107] A sensitivity of total energy consumption (i.e. energy cost) with respect to sampling time and window length, W , under the present embodiment is shown in Figure 5. In this embodiment, each zone module 12 generates token requests over various future time windows up to W hours. Small sampling times result in peaks in the mass flow rate of cool air, with the supply fan 50 supplying a bulk of the token requests at the end of the pre-cooling period, which wastes energy in the supply fan 50. Large sampling times result in long pre-cooling periods, which waste energy in the chiller 36. Empirically, it was observed that a sampling time of 20 minutes resulted in the lowest total energy consumption of the simulated VAV system 30.

Comparison with Nonlinear Optimisation

[00108] Embodiments of the present invention solve the general scheduling problem described above in two stages: token requests and token allocation. It is possible to compare this strategy with a brute-force approach of single-stage centralised nonlinear optimisation. Such a nonlinear optimisation approach was applied to the same five

zone setup as described above and the results are shown in Figure 6A, B, C and D, for comparison with the present embodiment.

[00109] As above, Figure 6A shows the temperature profiles for each zone 34, Figure 6B shows the mass flow rate of cool air for each zone 34, Figure 6C shows the mass flow rate of cool air at the supply fan 50 and Figure 6D shows the power consumption for entire VAV system 30, P , the chiller 36, P_c , and the supply fan 50, P_f . In this case, the temperature profiles and mass flow rates of cool air in each zone 34 closely resemble those computed in the token-based approach according to the above embodiment of the invention, as shown in Figures 4A, B, C and D.

[00110] Differences in total energy consumption and computation time for each method are summarised in Table 3.

Algorithm	Computation time (seconds)	Energy Cost (kJ)	%difference
Nonlinear Optimisation	71	1688.7	1.6
Token-based Approach	1.9	1716.2	

Table 3: Nonlinear Optimisation vs. Token-based Approach

[00111] In this example, the total energy consumption with the token-based approach according to an embodiment of the present invention is only sub-optimal (compared to the nonlinear optimisation approach) by 1.6%. However, the computation time for the token-based approach is significantly lower by a factor of 35 for only 5 zones. Further simulations have revealed even more dramatic computational savings for buildings with 100 or more zones 34 and with still only modest sub-optimal performance in terms of total energy consumption. In the present studies, the token-based approach according to embodiments of the present invention could comfortably accommodate the realistic case of 500 zones 34. However, for these larger simulations, it was not possible to have an “optimal” baseline available as the nonlinear optimisation approach described above failed at around 130 zones 34 due to the large computation required.

Comparison with Legacy Pre-cooling Strategy

[00112] A legacy pre-cooling strategy for commercial buildings is to commence cooling at a fixed time each day. In this example, an acceptable temperature range for all zones 34 is identical and assumes occupancy over the working day (9am to 6pm). In this case, a pre-cooling period was 30 minutes in advance of the start of the working

day at 9am. This pre-cooling period was uniform across all zones 34 in the building and the mass flow rate of cool air to each zone 34 was also pre-set to be constant across the pre-cooling period. This legacy pre-cooling strategy was simulated to offer a further point of comparison with embodiments of the present token-based approach as described above.

[00113] Figure 7A shows the temperature profile for a single zone 34, Figure 7B shows the mass flow rate of cool air at the supply fan 50 and Figure 7C shows the power consumption for the VAV system 30, P , the chiller 36, P_c , and the supply fan 50, P_f under this legacy pre-cooling strategy. In this case, there is clearly a large peak in the mass flow rate of cool air at the start of the pre-cooling period.

[00114] To compare the legacy pre-cooling strategy with the present embodiment token-based approach, an acceptable temperature range for all zones of 21-24°C was used and Table 4 compares the total energy consumption (i.e. energy cost) under each approach. Thus, the token-based approach has a lower energy consumption and realises an 18.9% saving in total energy use when compared to the legacy pre-cooling strategy.

Algorithms	Energy Cost (kJ)	% Savings		
Legacy Precooling Strategy	2014.44	18.9	Chiller	64.4
Token-based Approach	1633.90		Fan	35.6

Table 4: Token-based Approach vs. Legacy Pre-cooling Strategy

Results: Example 1

[00115] The present small-scale simulation examples reveal the promise of embodiments of the present invention. Considerable energy savings are realised over the legacy pre-cooling strategy and the total energy consumption is only 1-2% larger than the benchmark under centralised nonlinear optimisation, while the computation time is smaller by a factor of 35.

[00116] The most compelling advantages of embodiments of the present invention are derived from: (a) its scalability to realistically large commercial buildings, (b) its robustness to occupancy or cooling load changes, and (c) importantly, its low deployment cost.

[00117] Future improvements to the models and equations may comprise incorporation of pressure constraints in the VAV AHU 40, consideration of coefficient-of-performance functions for the chillers/heaters 36 (as described below), accommodation of multiple chillers 36 and chiller staging and assessing fault detection and isolation functionality.

[00118] Further embodiments of the present invention (such as those described below) may be configured to readily accommodate chiller 36 efficiencies through Coefficient of Performance (COP) specifications, as well as constraints on the mass flow rates of cool air, supply fan 50 capacities, duct 32 pressure distribution, and damper 52 opening constraints.

Example 2

Example 2 describes an elaborated scheduling problem similar to that of example 1 but with a consideration of chiller COP and feasibility of incorporating air duct pressure distribution.

In-building Air Distribution System

[00119] Figure 8 illustrates a further embodiment of a BEMS according to the present invention which also utilises a token-based approach similar to that described above, but taking chiller COP and air duct pressure distribution into account. In particular, Figure 8 shows an in-building section of a Variable Air Volume (VAV) HVAC system 60 which is similar to that shown in Figure 2. The HVAC system 60 comprises an Air Handling Unit (AHU) 62 that takes outside air and performs multiple functions like filtration, temperature control and humidity control, etc. After passing through filters 64, the outside air is mixed (into mixed air) in a mixing chamber 66 with return air from inside building zones. This process is vital for maintaining indoor air quality (e.g. in relation to CO₂ levels) for occupants. The mixed air passes around cooling coils 68 that circulate chilled water supplied by chillers (not shown). A mass flow rate and temperature of the chilled water is controlled to ensure that the mixed air is cooled to a predetermined temperature forming cool air, suitable for cooling the building zones.

[00120] The mixed air incoming to the cooling coils 68 is relatively warm and exchanges heat with the chilled water in the cooling coils 68 within the AHU 62 as described previously. The cool air outgoing from the cooling coils 68 is forced by supply fan 70 into the building's supply duct 72. A pressure rise at the supply fan 70 depends

on the mass flow rate of cool air which, in turn, is determined by a cooling demand of the building zones.

[00121] The zones 74 in this embodiment are conditioned spaces inside the building that are regulated by a single thermostat. Each zone 74 has a duct opening fitted with a set of metal plates called dampers 76 that control a cross sectional area of the duct openings, affecting the mass flow rates of cool air entering the zones 74. Within each zone 74, the cool air incoming through the damper 76 mixes with existing air in the zone 74 reducing an overall zone 74 temperature. A return duct 78 transports air from each zone 74 and vents a portion of the air in the return duct 78 to outside the building, while a remainder of the air in the return duct 78 is fed into the mixing chamber 66 for re-circulation.

[00122] As per Figure 1B, in this embodiment, the HVAC system 60 comprises zone modules 12 configured to compute token requests for minimum mass flow rates of cool air, which are communicated to a centralised scheduler 14 configured for token allocation and control of the HVAC system 60 components to deliver the required mass flow rates of cool air to each zone 74, in accordance with Figures 1A and 1B. Notably, in this embodiment, the coefficient-of-performance functions for the chiller are taken into account by the centralised scheduler 14 when minimising energy consumption of the HVAC system 60.

Component Models

[00123] As before, the present embodiment concentrates on commercial buildings, where employees would have relatively fixed working hours and temperature set-points for zones 74 are stable and predictable. Humidity is not considered, air mixing inside building spaces is assumed to be instantaneous, and local weather forecasts are provided as inputs to the local models in each zone module 12.

Zone Module Local Model

[00124] In this embodiment the simple bilinear local model described above is used with decoupled thermal dynamics across zones 74. As above, zone temperature set-points for each zone 74 are specified in advance. Instead of a strict zone set-point, a range of temperatures that are within human comfort requirements such as those depicted in Table 1 are employed. As before, a model predictive control strategy is employed to deal with both increasing forward uncertainty in the weather forecasts, as

well as abrupt changes in the zone temperature set-points (possibly from occupancy forecasts or zone environmental sensor 20 data).

Duct Network

[00125] In the present embodiment, the mass flow rate of cool air for each zone 74 is scheduled by the centralised scheduler 14 and the HVAC system 60 is operated to ensure that a pressure rise due to the supply fan 70 and damper 76 positions deliver the scheduled mass flow rate of cool air to each zone 74.

[00126] A schematic of an air supply duct network 80 employed in the present embodiment is presented in Figure 9 and comprises a supply fan 82 coupled to a main duct 84 from which branch ducts 86 carry supplied air to each room in the building. In this case, each branch duct 86 splits into two arms 88 to feed air into duct openings in each room through two separate dampers (not shown). An area fed by each damper therefore constitutes a zone 90 in this embodiment.

[00127] A pressure in the duct network 80 is given by Equation (17):

$$\Delta p = a \frac{\dot{m}^2}{A^{5/2}} \quad (17)$$

where a is a constant, A is the cross-sectional area of the duct network 80, and $\dot{m}$ is the mass flow rate of the supplied air.

[00128] In the main duct 84, the cross sectional area is assumed to be the same throughout the duct network 80 and hence, pressure at the main duct 84 can be simplified as follows:

$$\Delta p = f \dot{m}^2 \quad (18)$$

where $f = \frac{a}{A^{5/2}}$ is a constant.

[00129] Pressure decreases from p_0 to p_{n_z} in the main duct 84, where n_z is the number of zones 74, p_i is pressure at zone i , and p_0 is pressure at an outlet of the supply fan 82. Considering a particular mass flow rate of cool air that has to be satisfied, corresponding pressure requirements at the main duct 84 would be given as per Equation (19):

$$p_{i+1} - p_i + f \left(\sum_{q=i+1}^{n_z} \dot{m}_q \right)^2 = 0, \quad i = 0, 1, 2, \dots, n_z - 1 \quad (19)$$

[00130] This equation gives the relationship between pressure in the main duct 84 and mass flow rate of cool air flowing through it in the absence of dampers or when all dampers are in a fully open position. As there exists an extra control due to the dampers in the duct openings to each zone 74, an increase in the pressure in the main

duct 84 need not alter the mass flow rate of air in each zone 74 since the damper positions can be adjusted for each zone 74 as required. Thus, even if the pressure is increased in the duct network 80, the same mass flow rate of cool air could be maintained by closing dampers at the zones 74 accordingly.

[00131] In relation to the duct openings (i.e. dampers) the pressure of every zone 74 may initially be considered to be the same constant value p_z . At every duct opening, there is a damper fitted in the present embodiment, which alters the cross-sectional area A_i of the duct network 80 in order to control the mass flow rate of cool air passing through it.

[00132] A pressure equation for each duct opening fitted with a damper is given in Equation (20):

$$p_i - p_z = \frac{a}{A_i^{5/2}} \dot{m}^2 \quad (20)$$

where A_i is cross sectional area of the duct opening for zone i . Expressing this with inequalities gives us Equations (21) and (22):

$$\dot{m}^2 \geq \frac{A_i^2}{a} [p_i - p_z] \quad (21)$$

$$\dot{m}^2 \leq \frac{\overline{A_i^2}}{a} [p_i - p_z] \quad (22)$$

where $\underline{A_i}$ is the minimum cross-sectional area of the duct opening and $\overline{A_i}$ is maximum cross-sectional area of the duct opening.

Supply Fan

[00133] Referring back to Figure 8, as an example, the power consumed by the supply fan 70 depends mainly on the mass flow rate of the cool air passing through it and the pressure difference between an inlet and an outlet of the supply fan 70 as defined in Equation (23).

$$P_f = (\sum_{i=1}^{n_z} \dot{m}_i) \frac{\Delta p}{\rho \eta_f} \quad (23)$$

[00134] As described previously, $\Delta p \propto (\sum_{i=1}^{n_z} \dot{m}_i)^2$, if damper 76 positions are fixed. This relation is not true when damper 76 positions are changed. The pressure difference increases more slowly than a total flow squared when dampers 76 are opened. Thus, a quadratic supply fan 70 power model is commonly used as per Equation (24):

$$P_f = k_f (\sum_{i=1}^{n_z} \dot{m}_i)^2 \quad (24)$$

[00135] A capacity of each supply fan 70 may also be considered in each application.

Chiller

[00136] The chiller 36 is a key component of a building HVAC system, responsible for removing heat from the building spaces and, as described above in relation to Figure 2, provides a continuous supply of chilled water 38 to cooling coils in an AHU 50, which cools air passing over the cooling coils.

[00137] Large buildings are equipped with multiple chillers 36 operating in parallel to meet large cooling requirements. The most important factor that determines performance of the chillers 36 is a load carried by each operating chiller 36. A variety of chiller 36 sequencing control methods are practiced for switching the chillers on and off. The operating chillers 36 should provide sufficient cooling capacity at the best operating point possible for a given load condition. Total cooling load-based chiller 36 sequencing control determines thresholds according to a building instantaneous cooling load and a maximum chiller 36 cooling capacity, which is in principle the best approach for chiller 36 sequence control.

[00138] A coefficient of performance (COP) is the ratio of heating or cooling provided with respect to electrical energy consumed. Higher COPs equate to lower operating costs. In the present embodiment, the COP of the chiller (not shown in Figure 8) is considered to be a piecewise constant function of a building cooling load. In this embodiment, η is denoted as a reciprocal of the COP, g_i is a cooling energy provided to zone i , and Q_{ch} is a constant that denotes various amounts of cooling loads.

$$\eta = \begin{cases} \eta_1 \text{ if } \sum_{i=1}^{n_z} g_i \leq Q_{ch1} \\ \eta_2 \text{ if } Q_{ch1} < \sum_{i=1}^{n_z} g_i \leq Q_{ch2} \\ \eta_3 \text{ if } Q_{ch2} < \sum_{i=1}^{n_z} g_i \leq Q_{ch3} \\ \dots \end{cases}$$

[00139] In the present embodiment a simple control-oriented model is used to determine the power consumption of the chiller, which, for ease of reference is similar to the chiller 36 depicted in Figure 2, as drawn from equation (25) below:

$$P_c = c_p \eta \sum_{i=1}^{n_z} \dot{m}_i (T_m - T_c) \quad (25)$$

where a mixed air temperature is $T_m = (1 - d_r)T_{oa} + d_r T_r$, a return air temperature is $T_r = \frac{\sum_{i=1}^{n_z} \dot{m}_i T_i}{\sum_{i=1}^{n_z} \dot{m}_i}$ and d_r is a return air to mixed air ratio. Therefore, the power consumption of the chiller 36 is given by Equation (26):

$$P_c = c_p \eta ((1 - d_r)(T_{oa} - T_c) \sum_{i=1}^{n_z} \dot{m}_i + d_r \sum_{i=1}^{n_z} \dot{m}_i (T_i - T_c)) \quad (26)$$

[00140] The power consumption is not linear in the mass flow rate of cool air $\dot{m}_i$ as the zone temperature T_i also depends on $\dot{m}_i$ through the zone module's local model described above.

[00141] The dominant term in the objective function is the cooling energy. For $d_r \approx 1$, substituting from (8) results in Equation (27):

$$P_c \approx c_p \eta \sum_{i=1}^{n_z} g_i \quad (27)$$

which is linear in the decision variables g_i when η is a constant. $\sum_{i=1}^{n_z} g_i$ is interpreted as a building cooling load. Using a simple approximation, $T_{oa} \approx T_i$, Equation (26) becomes:

$$P_c \approx c_p \eta \sum_{i=1}^{n_z} \dot{m}_i (T_i - T_c) \quad (28)$$

[00142] Besides the chiller 36 COP, a capacity of the chiller 36 is another constraint that may be considered in embodiments of the invention. Such a linear constraint that couples all zones 74 can be easily handled by using Lagrangian relaxation. However, for ease of illustration this constraint is not considered further in this example.

Token Based Scheduling

[00143] The present embodiment has an architecture similar to that depicted in Figure 1B and described above. Thus, the zone modules 12 operate in parallel to model the thermal dynamics of each zone 74 independently and to compute token requests (e.g. in the form of minimum energy cooling requirement profiles) for each zone 74 which are relayed to the centralised scheduler 14.

[00144] The centralised scheduler 14 receives the token requests and allocates them to each zone 74. In this embodiment, the work of the centralised scheduler 14 is in two steps. The first step concerns only the coefficient of performance (COP) of the chiller 36. An optimisation algorithm is configured to increase the cooling energy supplied to each zone 74 and improve the COP of the chiller 36, hence reducing overall energy consumption. This computation reduces to a mixed integer linear programming problem and the token requests are expressed as cool air mass flow rate tokens to be allocated by the centralised scheduler 14 to provide a token allocation for each zone 74.

[00145] The second step of the centralised scheduler 14 is to check damper 76 constraints and identify an optimal pressure profile for the duct network 80, such as that illustrated in Figure 9, for the next time-slot. Damper 76 settings are adjusted to regulate a flow of cool air to each of the zones 74. The power consumption of the supply fan 70 is also considered in this step. The token allocation attempts to minimise total energy consumption while respecting operational constraints and reduces to a constrained quadratic programming problem. Zone modules 12 update their local models based on measured thermal response (e.g. from sensors in each zone) as a result of the allocated tokens and re-compute forward token requests for subsequent time-slots in a Model Predictive Control framework, as before. A huge reduction in computation time over the prior art can be expected from both parallel optimisation of the zone modules 12 and a hierarchical architecture concerning the token requests and the subsequent token allocation. The reduced complexity ensures that the architecture is scalable to large buildings (e.g. containing 300-500 zones).

Zone Module and Centralised Scheduler Algorithms

[00146] Bemporad and Morari proposed a framework for modelling mixed logical dynamical systems, which can be transformed into linear dynamic equations subject to linear inequalities involving real and integer variables. This framework is employed in the present embodiment to deal with the COP constraints of the chiller 36. In this case, equation (29) is followed:

$$\eta(k) = \begin{cases} \eta_1 \text{ if } \sum_{i=1}^{n_z} g_i(k) \leq Q_{ch1} \\ \eta_2 \text{ if } Q_{ch1} < \sum_{i=1}^{n_z} g_i(k) \leq Q_{ch2} \\ \eta_3 \text{ if } Q_{ch2} < \sum_{i=1}^{n_z} g_i(k) \leq Q_{ch3} \\ \eta_4 \text{ if } Q_{ch3} < \sum_{i=1}^{n_z} g_i(k) \leq Q_{ch4} \\ \eta_5 \text{ if } \sum_{i=1}^{n_z} g_i(k) > Q_{ch4} \end{cases} \quad (29)$$

Furthermore, Boolean variables δ are introduced for proper selection of η defined as:

$$\begin{aligned} \forall k, \delta_1(k) &\leftrightarrow \sum_{i=1}^{n_z} g_i(k) \leq Q_{ch1} \\ \forall k, \delta_2(k) &\leftrightarrow \sum_{i=1}^{n_z} g_i(k) \leq Q_{ch2} \\ \forall k, \delta_3(k) &\leftrightarrow \sum_{i=1}^{n_z} g_i(k) \leq Q_{ch3} \\ \forall k, \delta_4(k) &\leftrightarrow \sum_{i=1}^{n_z} g_i(k) \leq Q_{ch4} \end{aligned} \quad (30)$$

[00147] Such logical conditions can be rewritten as linear relations using known methods:

$$[f(x) \leq 0] \leftrightarrow [\delta = 1] \text{ is true if } f(x) = \begin{cases} f(x) \leq U(1 - \delta) \\ f(x) \geq \epsilon + (u - \epsilon)\delta \end{cases} \quad (31)$$

where $U \triangleq \max f(x)$, $u \triangleq \min f(x)$ and ϵ is a small tolerance beyond which the constraint is considered violated. Equation (27) for the power consumption of the chiller 36 becomes:

$$P_c(k) = \delta_1(k)\eta_1 \sum_{i=1}^{n_z} g_i(k) + (\delta_2(k) - \delta_1(k))\eta_2 \sum_{i=1}^{n_z} g_i(k) + (\delta_3(k) - \delta_2(k))\eta_3 \sum_{i=1}^{n_z} g_i(k) \\ + (\delta_4(k) - \delta_3(k))\eta_4 \sum_{i=1}^{n_z} g_i(k) + (1 - \delta_4(k))\eta_5 \sum_{i=1}^{n_z} g_i(k) \quad (32)$$

and any $\delta f(x)$ can be replaced by an auxiliary real variable $y = \delta f(x)$, which is equivalent to:

$$\begin{aligned} y &\leq U\delta \\ y &\geq u\delta \\ y &\leq f(x) - u(1 - \delta) \\ y &\geq f(x) - U(1 - \delta) \end{aligned} \quad (33)$$

Zone Module Token Requests

[00148] The zone modules 12 receive zone environmental sensor data from the available sensors 20 in the zones 74. In addition to standard thermostats, this could include information from occupancy sensors, mass flow rate sensors, and damper 76 position sensors. The zone module 12 may also be informed about weather forecasts and occupancy predictions for its zone 74.

[00149] As explained above, each zone module 12 solves the following optimisation problem for a fixed time planning horizon H_p using Equation (34) subject to Equations (35) and (36):

$$J_1(H_p) = \min \sum_{k=1}^{H_p} g_i(k) \quad (34)$$

$$T_i(k+1) + \alpha_1 T_i(k) + \alpha_2 g_i(k) = v_i(k) \quad (35)$$

$$T_{il}(k) \leq T_i(k) \leq T_{ih}(k) \quad (36)$$

[00150] As before, $T_i(k)$ is a linear function of the decision variables $g_i(s)$; $s \leq k$ because the dynamics in Equation (35) are linear. Thus, a linear programming problem is established which can be solved quickly due to parallel computation in all zones.

[00151] The solution g_i^* is sent to the centralised scheduler 14 as cooling energy token requests: $TokA(k) = g_i^*(k)$ for $k = 1, 2, \dots, W$, where W is a set window size for the planning horizons.

Incorporating Chiller COP

[00152] The power consumption of the chiller 36 depends on the building cooling load as derived earlier in Equation (27). As explained above, most buildings have a set of more than one chiller 36 following a scheduling algorithm to attain maximum efficiency at any given cooling load. Energy savings in incorporating COP into the present embodiment may not be significant over a small time period like a day or a week, but annual savings may be significant. For a fixed window size W , the centralised scheduler 14 in the present embodiment solves a mixed integer linear programming problem as defined in Equation (37) subject to Equations (38) to (49).

$$\min \sum_{k=1}^W \sum_j^{n_j} D_j(k) \quad (37)$$

$$\forall i, k, g_i(k) \geq TokA(K) \quad (38)$$

$$\forall k, j, \delta_{ij}(k) \in \{0,1\} \quad (39)$$

$$\forall k, j = 1, 2, \dots, n_j - 1, \sum_{i=1}^{n_z} g_i(k) - Q_{chj} \leq U_j(1 - \delta_j(k)) \quad (40)$$

$$\forall k, j = 1, 2, \dots, n_j - 1, \sum_{i=1}^{n_z} g_i(k) - Q_{chj} \geq \epsilon + (u_j - \epsilon)\delta_j(k) \quad (41)$$

$$\forall k, j = 1, 2, \dots, n_j - 1, D_j(k) \leq U\delta_j(k) \quad (42)$$

$$\forall k, j = 1, 2, \dots, n_j - 1, D_j(k) \geq u\delta_j(k) \quad (43)$$

$$\forall k, j = 2, \dots, n_j, D_j(k) \leq U(1 - \delta_{j-1})(k) \quad (44)$$

$$\forall k, j = 2, \dots, n_j, D_j(k) \geq u(1 - \delta_{j-1})(k) \quad (45)$$

$$j = 1, \dots, n_j - 1, \forall k, D_j(k) \leq \eta_j d_r(k) \sum_{i=1}^{n_z} g_i(k) - u(1 - \delta_j(k) + \sum_{l=1}^{j-1} \delta_l(k)) \quad (46)$$

$$j = 1, \dots, n_j - 1, \forall k, D_j(k) \geq \eta_j d_r(k) \sum_{i=1}^{n_z} g_i(k) - U(1 - \delta_j(k) + \sum_{l=1}^{j-1} \delta_l(k)) \quad (47)$$

$$\forall k, D_{n_j}(k) \leq \eta_{n_j} d_r(k) \sum_{i=1}^{n_z} g_i(k) - u(\sum_{l=1}^{n_j-1} \delta_l(k)) \quad (48)$$

$$\forall k, D_{n_j}(k) \geq \eta_{n_j} d_r(k) \sum_{i=1}^{n_z} g_i(k) - U(\sum_{l=1}^{n_j-1} \delta_l(k)) \quad (49)$$

where $U_1(k) = \max \sum_i g_i(k) - Q_{ch1}$, $u_1(k) = \min \sum_i g_i(k) - Q_{ch1}$, and so on. A quadratic cost function (32) is converted to a mixed integer linear one by applying Equations (33) and introducing constraints (42)-(49). Constraint (38) ensures that the minimum cooling energy token request is satisfied. Boolean variables defined in (39) are introduced to convert the constraints (30) to linear constraints (40)-(41) using condition (31).

Mass Flow Rate Constraints

[00153] Similar to the treatment in Example 1, in this embodiment, the planning horizon H_w is fixed and $g_i^{opt}(k)$ is an optimal cool air token request that solves the

mixed integer linear Equation (37). Using linear dynamics from Equation (35), it is possible to compute an associated optimal temperature profile $T_i^{opt}(k)$. As before, using Equation (8), it is possible to translate the token request into a mass flow rate request as below:

$$\dot{m}_i^{opt}(k) = \frac{g_i^{opt}(k)}{(T_i^{opt}(k) - T_c)}, k = 1, \dots, H_w$$

and the corresponding minimum total mass flow rate of cool air on the planning horizon required for zone i is computed as:

$$TokB_i(H_w) = \sum_{k=1}^{H_w} \dot{m}_i^{opt}(k), H_w = 1, \dots, W$$

[00154] It is possible to interpret $TokB_i(H_w)$ as the minimum number of tokens needed by zone i on the planning horizon H_w to meet its local temperature constraints. Information carried by the tokens is twofold: an amount of cooling required and an urgency of the cooling required. For a single planning horizon ($H_w = W$), $TokB_i(H_w)$ does not convey the urgency of the token requests. To capture this, the token requests are generated for various planning horizons $H_w = 1, 2, \dots, W$ such that $TokB_i(1)$ is the minimum number of tokens needed in the first sample period, $TokB_i(2)$ in the first two periods, and so on. Thus, the token requests may be grouped into a profile $TokB_i(H_w)$ of computed token requests for different planning horizons to capture the urgency of the cooling required for zone i.

Centralised Scheduler Token Allocation

[00155] A final step of the present token based approach concerns the supply fan 82 (or supply fan 70), and the duct network 80. A cost function is the power consumption of the supply fan 82 and the decision variables are p_0 , p_i and $\dot{m}_i \forall i$.

[00156] The supply fan 82 has a power function that is non-linear (usually quadratic or cubic) in relation to the mass flow rate of supply air at the AHU 62 and flattening of the mass flow rate of supply air at the AHU 62 $\dot{m}_{SA}$ profile could lead to savings at the supply fan 82 level. However, this may not be a high priority as the power consumption of the chiller 36 is linear in $\dot{m}_{SA}$ and much larger than the supply fan's 82 power consumption.

[00157] Feasibility of delivering the requested mass flow rate of cool air to each zone 74 may be considered with respect to pressure distribution in the duct network 80 through analysis of the equations (19), (21) and (22).

[00158] In this embodiment, a convex approximation to a pressure model of a building is assumed and the dampers 76 at the duct openings of the zones 74 are designed to not completely close at any time. As long as the supply fan 82 is running, a small amount of cool air enters a zone 74 captured by a non-zero damper 76 opening in Equation (21). As this is a non-convex equation, it is converted into a convex one by linearising the equation as it represents only a very small value of $\dot{m}_i$ below 1 as given by Equation (52). Equations (19) and (22) represent further constraints in this step.

[00159] In this case, the duct network 80 shown in Figure 9 is considered and a distance between the duct openings of two zones 74 is assumed to be the same throughout. All zones 74 are assumed to be at the same pressure p_z and the centralised scheduler 14 solves Equation (50) below subject to constraints (51) to (56).

$$\min k_f \sum_{k=1}^{H_w} (\sum_i \dot{m}_i(k))^2 \quad (50)$$

$$H_w = 1, 2, \dots, W, i = 1, 2, \dots, n_z, \sum_{k=1}^{H_w} \dot{m}_i(k) \geq TokB(H_w) \quad (51)$$

$$i = 1, 2, \dots, n_z, k = 1 \dots H_w, p_i(k) - p_z - a \frac{\dot{m}_i(k)}{A_i^{5/2}} \leq 0 \quad (52)$$

$$i = 1, 2, \dots, n_z, k = 1 \dots H_w, p_i(k) - p_z - a \frac{\dot{m}_i^2(k)}{A_i^{5/2}} \geq 0 \quad (53)$$

$$i = 1, 2, \dots, n_z, k = 1 \dots H_w, p_i(k) \geq p_z \quad (54)$$

$$k = 1 \dots H_w, p_{i+1}(k) - p_i(k) + f(\sum_i \dot{m}_i(k))^2 \leq 0 \quad (55)$$

$$k = 1 \dots H_w, p_0(k) \leq p_{cap} \quad (56)$$

[00160] Cool air only flows from the duct openings into the zones 74 if Equation (54) is satisfied. A maximum pressure at the supply fan 82 is capped at p_{cap} given by Equation (56). The above problem is an example of Quadratic Constrained Quadratic Programming (QCQP) which can be solved by an IBM ILOG CPLEX Optimiser.

Simulation Studies

[00161] The token-based approach of example 2 for the present embodiment of the invention was implemented in Matlab R2014a on a PC with Intel Core i7 processor, 8GB RAM and 64-bit Operating System. The parameter setup for the simulations is the same as that provided above in Table 2 and Figures 3A, 3B and 3C. In addition, Figure 10 shows the reciprocal of coefficient of performance (COP) for the chiller 36, η , as obtained from manufacturer datasheets.

[00162] In relation to a previous embodiment described above (in example 1), a comparison of a simulated embodiment of the present invention was made with

existing strategies including centralised non-linear optimisation and legacy pre-cooling. The token-based approach of example 1 that is used in these comparisons may be further extended using the more general embodiment described above where the equations take into account the chiller 36 COP and the pressure distribution of the duct network 80.

Case 1: Comparison with Centralised Nonlinear Scheduling

[00163] Results from example 1's token based approach described above (without COP) were previously compared with a centralised nonlinear approach that can be regarded as the optimal energy minimising strategy.

[00164] Comparisons of energy consumption and computation time for buildings with various different numbers of zones 34 are summarised in Table 5. It can therefore be seen that the token based approach of example 1 is suboptimal by approximately 2%. However, this is negligible compared to the computational advantage gained, and importantly, the modular simplicity of the architecture proposed. An advantage of the token-based approach is its scalability to large buildings as becomes evident with a large number of zones 34. The centralised non-linear optimisation approach completely fails to converge for more than 100 zones 34 but the computation time for the token-based approach of example 1 is still low.

Algorithm	Computation time (seconds)			Energy Cost (kJ)	
	50 zones	120 zones	400 zones	6 zones	15 zones
Token-based Approach	0.019	0.046	0.76	1990.4	5594.9
Centralised nonlinear optimisation	560	-	-	1950.3	5476.5

Table 5: Comparison of Token-Based v Nonlinear Optimisation Approaches

Case 2: Comparison with Legacy Pre-Cooling

[00165] In this legacy pre-cooling example, pre-cooling of building spaces began at a fixed time for all zones 34 before the expected arrival of the first occupants. The mass flow rate of cool air supplied during the pre-cooling period was constant and the pre-

cooling period was typically around 30-45 minutes. All zones 34 were pre-cooled at the same time. The zone temperature demands were not handled individually. This example was implemented in MATLAB for six zones to compare it with the token-based approach described above for embodiments of the present invention in accordance with example 1. For a better comparison, the token-based approach was implemented for zones with the same temperature requirements but with varying service times.

[00166] In essence, the results of the legacy pre-cooling approach were as shown in Figures 7A, 7B and 7C while the results of the present token-based approach in accordance with an embodiment of the invention are shown in Figures 11A, 11B and 11C.

[00167] In summary, Figures 7A and 11A show the difference in temperature trajectories between both approaches. The token based approach only supplies enough cool air to satisfy a minimum cooling requirement whereas the legacy pre-cooling approach satisfies the temperature demands, but cools zones 34 that are not even in service. The saving in terms of energy consumption for the present embodiment is 17%. The following table shows more details about this comparison.

	Energy consumption(kJ)	Percentage savings
Token-based scheduling	1878.62	17%
Legacy Pre-cooling approach	2263.40	

[00168] However, the amount of energy saving that can be expected for a given application will depend on the zone 34 service hours, temperature demands, and most importantly, the total number of zones 34 under consideration. It is expected that the greater the number of zones 34 under consideration, the higher the energy saving using embodiments of the present invention.

Commercial applications

[00169] It is expected that embodiments of the present invention such as the token-based approach described herein (with or without COP or duct pressure distribution considerations) will substantially reduce energy consumption across commercial buildings. Based on preliminary simulations, it is believed that a target of 20% energy savings using this approach is realistic. The architecture described above in relation to embodiments of the invention is applicable to all BEMS and is especially useful for VAV (Variable Air Volume) HVAC systems.

[00170] Although only certain embodiments of the present invention have been described in detail, many variations are possible in accordance with the appended claims. For example, features or steps associated with one embodiment or one example described above may be mixed and matched with features or steps associated with another embodiment or example of the invention.

References

[00171] The disclosure of the following references is incorporated in its entirety.

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Claims

1. A method of operating a building environment management system (BEMS) comprising:
 - a) obtaining zone environmental sensor data and zone set-points for each of two or more zones in a building;
 - b) computing, for each zone, a request for a minimum cooling/heating air supply rate to meet the zone set-points;
 - c) communicating the request for each zone to a scheduler;
 - d) receiving, at the scheduler, the request for each zone and energy efficiency data on one or more components of the BEMS;
 - e) balancing the requests against energy consumption of the one or more components of the BEMS for a subsequent time period;
 - f) calculating an air supply strategy based on the balancing of step e), the air supply strategy comprising a cooling/heating air supply allocation for each zone in the subsequent time period to minimise the energy consumption of the one or more components, while aiming to satisfy all zone set-point requirements; and
 - g) controlling the BEMS to deliver the allocation of step f) to each zone.
2. The method according to claim 1, wherein the one or more components of the BEMS comprises an air handling unit.
3. The method according to claim 2, wherein the one or more components of the BEMS further comprises a fan and/or damper associated with the air handling unit.
4. The method according to any preceding claim, wherein the one or more components of the BEMS comprises a chiller or heater.
5. The method according to any preceding claim, further comprising repeating steps a) to g) at pre-defined time-intervals.
6. The method according to any preceding claim, further comprising repeating steps a) to g) when zone environmental sensor data reaches a pre-defined value.

7. The method according to any preceding claim, wherein each request conveys an amount of cooling/heating required and an urgency of the request.
8. The method according to any preceding claim, wherein the requests are determined for multiple time periods.
9. The method according to claim 8, wherein the multiple time periods of the requests have a common start time and different end times.
10. The method according to claim 4, further comprising accounting for a coefficient of performance of the chiller/heater when minimising the energy consumption.
11. The method according to any preceding claim, further comprising accounting for air duct design constraints when minimising the energy consumption.
12. The method according to any preceding claim, wherein the zone set-points are determined by thermostat settings.
13. A building environment management system (BEMS) comprising:
 - a) two or more zone modules configured to:
 - i. obtain zone environmental sensor data and zone set-points for each respective zone;
 - ii. compute a request for a minimum cooling/heating air supply rate to meet the zone set-points within each respective zone; and
 - iii. communicate the request for each respective zone to a scheduler;
 - and
 - b) a scheduler configured to:
 - i. receive the requests for each zone and energy efficiency data on one or more components of the BEMS;
 - ii. balance the requests against energy consumption of the one or more components of the BEMS for a subsequent time period;
 - iii. calculate an air supply strategy based on the balance of step b) ii, the air supply strategy comprising a cooling/heating air supply allocation for each zone in the subsequent time period to minimise the energy consumption of the one or more components, while satisfying all zone set-point requirements; and

iv. control the BEMS to deliver the allocation of part iii) to each zone.

14. The system according to claim 13, further comprising zone sensors for obtaining the zone environmental sensor data which comprises one or more of temperature, air pressure, carbon dioxide (CO₂) concentration, humidity, occupancy, status of windows, and status of doors.

15. The system according to claim 13 or 14, further comprising a communication network infrastructure for communication between each zone module and the scheduler.

16. The system according to any one of claims 13 to 15, wherein the BEMS is configured to adjust damper or fan settings to regulate a flow of cool/hot air to the zones.

17. The system according to any one of claims 13 to 16, wherein each zone module comprises one or more mathematical models configured for predicting environmental conditions within the zone.

18. The system according to claim 17, wherein the models comprise forecasts of one or more of weather, cooling/heating load, zone set-points, and occupancy.