2019 18th European Control Conference (ECC)
Napoli, Italy, June 25-28, 2019

A Scalable Contract Based Approach for Integrating Building Flexibility to Energy Grids

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Abstract— **By arbitraging among consumer comfort margins, buildings energy consumption can be changed by providing flexibility to grids. To manipulate the buildings energy consumption, a new contract-based approach to for multi-zone building heating, ventilation and air-conditioning (HVAC) systems is proposed. The approach includes the real-time markets by changing buildings optimal consumption pattern based on triggers sent by the aggregator. Also to decrease the energy consumption of buildings, the user is allowed to select the time-slots and rewards are provided to the user for aggregating flexibility. The aggregator bundles flexibility from the buildings at different time-slots and sells in real-time markets. The idea in aggregator's problem is to maximize aggregator's profits by selling flexibility in real-time markets (RTM) while ensuring the provisioning of flexibility from the buildings through incentives. To address this problem, we formulate it as a distributed optimization problem and then provide a method to solve it which provides good scalability, a requirement for large commercial buildings with multiple zones to participate in RTM. We illustrate the scalability and performance of the contract-based approach and solution technique in a building with 200 zones. Also, user participation based on their time-preferences is included in the proposed optimization. Finally, a scalable technique is shown which can be adopted in existing building automation systems.**

Keywords- Contract based design, Building Energy Management System (BEMS), Heating, Ventilation and Air Conditioning (HVAC), Model Predictive Control (MPC).

I. INTRODUCTION

Traditionally, additional generators are operated by load-serving entities (LSEs) to match consumption and demand during peak periods. Increasing fuel prices and environmental concerns are making this option untenable. An alternative is to make the demand follow supply patterns by providing incentives and it is called *'supply following'* (SF). Smart buildings are essential for SF programs as their consumption can be changed by exploiting user comfort margins of Heating, Ventilation, and Air Conditioning (HVAC) systems. Such flexibility can be used for demand response programs, provisioning ancilliary services, or sold to the grid provided there are proper contractual frameworks. In order to harness the flexibility from buildings, a redesign to traditional HVAC control systems is required.

The Model Predictive Control (MPC) approach has emerged as a promising technique for building HVAC control because of its capability to embed predictions of future weather, occupancy, energy prices, cooling loads, and disturbances (e.g., see, [1], [2]). While control of building HVAC is not new, harnessing flexibility from buildings requires overarching the current capabilities to compute flexibility while meeting user preferences [3]. An approach to declare flexibility against financial incentives and meeting spatial constraints, i.e., temperature set-points and control limits was studied in [3]. The role of building flexibility to provide frequency regulation under the assumption that aggregator and building objectives are aligned to grid objectives for provisioning flexibility has been studied in [4]. In [4], [5] financial incentives are provided to motivate the user to provision flexibility towards ancillary services. The problem of providing optimal contracts using a bi-level optimization framework and simplification of the approach has been discussed in [6]. However, the analysis is limited to the aggregator viewpoint.

The use of dynamic contracts that looks beyond the aggregator level for selling the flexibility was studied in [7]. A Nash-bargaining-based airflow allocations strategy, a method to solve cooperative resource allocation problem, with an agent based framework with respecting spatial constraints was proposed in [8]. The investigation in [9] used real-prices from Swiss electricity market to study the participation of the buildings in providing ancillary services and proved that by motivating participation in retail markets the overall energy costs can be reduced. A contract based design approach for aggregating, trading, and distributing reserves was studied using hierarchical optimization in [10]. A three level approach was used to contract flexibility. However, the analysis was restricted to building level loads and not HVAC systems wherein the different zones influence energy usage. A distributed approach to contract flexibility using ADMM was studied in [11] for frequency reserve bidding.

A review of literature reveals that contract-based approach is emerging as a promising solution to the flexibility aggregation problem. Usually, at the building level a centralized optimization model is solved to provide flexibility without considering zone influences. Further, financial incentive stimulating user is used as an underlying assumptions. How-

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This research is funded by the Republic of Singapore's National Research Foundation through a grant NRF2015ENC-GBICRD001-057 to the Berkeley Education Alliance for Research in Singapore (BEARS) for the Singapore-Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST 2) Program. BEARS has been established by the University of California, Berkeley as a center for intellectual excellence in research and education in Singapore

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ever, users temporal preference to offer flexibility is more important. In contrast to existing works, this investigation introduces user preferences for providing flexibility within the contracts. This inclusion leads to a mixed integer linear program (MILP) which is difficult to solve with large number of decision variables thereby making the formulation less scalable to large commercial buildings. To overcome this, we propose a hierarchical approach wherein flexibility is computed in individual zones and the user preferences are considered at the central level. The main contributions of this investigations are:

(i) Definition of contracts for aggregating demand flexibility from buildings HVAC system considering user defined comfort bands and time-slots.

(ii) A hierarchical approach wherein each zone computes the baseline, upward and downward flexibility using a model predictive control approach. The computed flexibilities and user preferences are used by the Building Energy Management Systems (BEMS) to schedule the flexibility with user preferences.

(iii) We illustrate the proposed approach for its scalability and performance on buildings using simulations.

The paper is organized as follows. Section II presents the preliminaries and problem formulation. The contracts and solution approach are discussed in Section III. Section IV presents the simulation results and conclusions are discussed in Section V.

II. Problem Formulation

The focus of this investigation is the commercial building HVAC control due to their relatively higher consumption. The proposed system studied is a variable-air-volume controlled HVAC supplying air to multiple zones in a building. The energy consumption in HVAC system is due to fan and chillers. The Air Handling Unit (AHU) consumption can be varied by changing the fan speed and the power consumed is proportional to the mass-flow rate $\dot{m}$ and the static pressure rise ΔP across the AHU, i.e., the fan power P_f is given as

$$P_f = \dot{m}\Delta P. \tag{1}$$

Similarly, the chiller power depends on the mass flow rate of the chilled water in the cooling coils and the latent temperature, $C_w \Delta T_c$, absorbed by the air circulating in the building with C_w being the specific heat and ΔT_c being the temperature difference between the supply and return chilled water in the cooling coil. The chiller power consumption is given by

$$P_c = \dot{m}_w C_w \Delta T_c. \tag{2}$$

The total power consumed in the HVAC system is therefore given by

$$P_T = P_f + P_c. \tag{3}$$

The total power HVAC consumption is changed, by adjusting the mass-flow-rate $\dot{m}_j$ with $j \in \{1, 2, \dots, N_z\}$, where N_z denotes the number of zones. The system can provide flexibility by changing the way it consumes energy, i.e., by changing mass-flow rate of air to each zone and the chiller water flow to provide flexibility.

TABLE I

Nomenclature

Parameter	Definition
π^e	Constant energy prices (SGD/kWh)
π^v	Time-of-Use cost of energy in (SGD/kWh)
π^T	Total energy costs in (SGD/kWh)
$x_j(k)$	Temperature of zone j in ^{o} C Celcius
$Q_j(k)$	Internal heating energy generated in the zones in kWh
U_j	number of flexibility periods for zone j
C_w	Specific heat of water (kJ/kg^oC)
C_a	specific heat of air ($kJ/kg^oC)$
H^p	Prediction horizon of the nominal MPC
Variable	**Definition**
P_f	Fan power consumption in kW
$\dot{m}$	Air mass flow rate
ΔP	static pressure across the AHU
$\dot{m}_w$	Water flow rate in the chiller
P_c	Chiller Power in kW
$g_j(k)$	Thermal energy supplied to zone j in kW
$\Delta\ T_c$	Change in temperature of water across the chiller coil water outlet temperature -inlet temperature
P_T	Total power consumption in HVAC system in Kw
$y_j(h)$	binary indicator for showing the becoming ON status of flexibility for zone j and time h
$z_j(h)$	binary indicator for showing the becoming OFF status of flexibility for zone j and time h

A. Baseline Contract

The objective of MPC is to optimize the time-varying costs without violating the occupant comfort margins (temperature set-points) and physical constraints (actuator limits). The operating cost consists of two parts: fixed and variable time-of-use charges. The costs are generally published 24 hours in advance for a particular day based on market clearing prices in the day-ahead markets.

$$\pi^T = \pi^e + \pi^v \tag{4}$$

At each time instant h, MPC solves the following optimization problem to calculate the optimal mass-flow rate $\mathcal{M}_j = [\dot{m}_j(\delta), \dots, \dot{m}_j(\delta + H^p)]\ \forall j \in \{1, 2, \dots, N_z\}$, supplied to the zones while satisfying the user-defined comfort bands and actuator limits. Here, H^p denotes the prediction horizon. Considering δ to be the sampling time, we have

$$\begin{aligned}
&\min_{\mathcal{M}(\delta)} \sum_{\delta=h}^{H^p} \sum_{j=1}^{N_z} C^j(\dot{m}_j(\delta), \pi^\delta) \\
&s.t. \\
&x_j(\delta+1) = f_j(x_j(\delta), \dot{m}_j(\delta), v_j(\delta), Q_j(\delta)), \\
&x_j(\delta) \in \mathcal{X}_j(\delta), \\
&\dot{m}_j(\delta) \in \mathcal{U}_j(\delta) \quad \forall j \in \{1, \dots, N_z\}, \delta = \{h, \dots, H^p\},
\end{aligned} \tag{5}$$

where f_j models the system dynamics, v_j the thermal disturbances acting on the zone j, $\mathcal{M}(\delta) = [\dot{m}_j(\delta + 1) \cdots \dot{m}_j(H^p)] \quad \forall j \in \{1, \dots, N_z\}$ the cooling energy supplied to j^{th} zone, and C^j the linear cost proportional to (π^T) that varies linearly with respect to the cooling energy supplied to each zone, respectively. The sets $\mathcal{X}_j$ and

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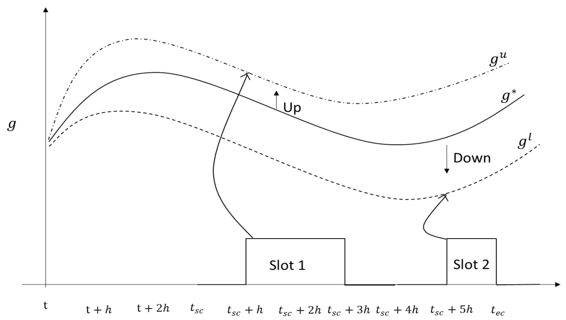

Fig. 1. Flexibility Illustration

$\mathcal{U}_j$ represents the bounds on system dynamics and mass-flow rate of zone j. The MPC solution defines the base-line contract, i.e., the nominal mass-flow rate for each zone. However, the zone thermal dynamical models are nonlinear and this increases the complexity to solve it using centralized approaches. To overcome this complexity, we define the cooling energy of the j^{th} zone as in [1], [12],

$$g(\delta) = C_a \dot{m}(\delta)\ (T(\delta) - T_{out}(\delta)) \quad \forall \delta \in \{h, \dots, H^c\} \quad (6)$$

where T_{out} models the temperature at the outlet of the AHU, and $T(t)$ is the temperature of mixed air chamber of the cooling coil. Consequently, the solution to the MPC can be written in terms of the g. Thus the power consumed by HVAC is computed as

$$C^{HVAC}(\delta) = \sum_{j=1}^{N_z} (\pi^e + \pi^v(\delta)) P_T(g_j(\delta)). \quad (7)$$

For using the building thermal flexibility, the optimal energy profiles $P_T(g^*)$ should be changed either upwards or downwards. The flexibility offered by the zones can be defined in terms of two envelopes $\vec{g^l} = [g^l_{sc} \cdots g^l_{ec}]$ and $\vec{g^u} = [g^u_{sc} \cdots g^u_{ec}]$ which are computed by solving the MPC formulation in (5) with user defined bounds as the references to be tracked. By declaring the flexibility each zone authorizes BEMS to select any power trajectory $P_T(\vec{u}) = [P_T(G_{tsc}), \dots, P_T(G_{tec})]$ such that $P_T(G^l(h)) \leq P_T(G(h)) \leq P_T(G^u(h)) \quad \forall h \in \{t_{sc}, t_{sc}+\delta, \dots, t_{ec}\}$ where t_{sc} and t_{ec} denote the starting and ending time of the contract. The flexibility can hence be defined as

$$Flexibility(t) \triangleq P_T(G^u(h)) - P_T(G^l(h)). \quad (8)$$

The concept of aggregating flexibility from a single zone in the building is illustrated in Fig.1. User can select time-slots to provide flexibility either upward or downward depending on the grid requests. In Fig.1 zone commits upward flexibility in two time-slots, i.e., $t_{sc}+h - t_{sc}+3h$ and downward flexibility for one slot $t_{sc}+5h - t_{ec}$. These requests are made announcing the rewards during the time period.

B. Temporal Constraints

The temporal constraints are required to model the user preferences for providing the flexibility. Each zone j in the building commits U_j flexibility slots. In addition, we denote the total time-horizon considered for providing flexibility as H^c, we have the following conditions

$$\begin{aligned} & t_{sc} \geq 1 \\ & t_{sc} + \delta \leq t_{ec} \\ & t_{ec} - t_{sc} \leq H^c \end{aligned} \quad (9)$$

where t_{sc} and t_{ec} denote the starting and ending time of the contract. Typical values of H^c is from 1-6 hours. Defining the binary variable I_j to denotes the flexibility is provisioned or not during a particular time-slot δ, we have

$$\mathbf{I}_j = [I_j(h), I_j(h+1), \dots, I(H^c)] \quad (10)$$

To restrict the number of slots of the flexibility to lie within the allowable time interval of the contracting period, we have

$$\sum_{j=1}^{N_z} \sum_{h=1}^{H^c} I_j(h) = U_j \quad \forall h \in \{1, \cdots, H^c\} \quad (11)$$

The constraint that some zones present flexibility in continuous slots is modelled as [13].

$$\sum_{j=1}^{N_z} \sum_{h=1}^{h=H^c+U_j-1} I_j(h) \geq U_j y_j(h) \quad \forall h \leq H^c - U_j + 1$$

where $y_j(h)$ is the binary indicator that indicates the zone j is offering flexibility and considering $z_j(h)$ to be the indicator for stopping flexibility. The flexibility status information is,

$$\sum_{j=1}^{N_z} \sum_{h=1}^{H^c} y_j(h) - z_j(h) = I_j(h) - I_j(h-1), \quad (12)$$

It is obvious that

$$\sum_{j=1}^{N_z} \sum_{h=1}^{H^c} y_j(h) + z_j(h) \leq 1. \quad (13)$$

C. Flexibility Model

Optimization model for providing flexibility with user preferences is given by,

$$\begin{aligned} \min_{\mathcal{G}_j(h), I_{jh}, y_{jh}, z_{jh}} & \sum_{\delta=h}^{H^p} C^{HVAC}(m_j(\delta), \pi^\delta, I_j(\delta), y_j(\delta), z_j(\delta)) \\ & - \sum_{\gamma=h}^{H^c} max(0, \overline{\mathcal{R}}(\gamma)\overline{\Phi}(g_j(\gamma), g^u(\gamma))) I_j(\gamma) \\ & - \sum_{\gamma=h}^{H^c} max(0, \underline{\mathcal{R}}(\gamma)\underline{\Phi}(m_j(\gamma), g^l\gamma))) I_j(\gamma) \end{aligned}$$

$s.t.$

$$\begin{aligned} & x_j(\delta+1) = f_j(x_j(\delta), m_j(\delta), v_j(\delta), Q_j(\delta)), \\ & \qquad \forall j \in \{1, \cdots, N_z\}, \delta = \{h, \cdots H^p\} \\ & x_j(\delta+1) \in \mathcal{X}_j(\delta) \quad \forall j \in \{1, \cdots, N_z\}, \\ & m_j(\delta+1) \in \sqcap_j(\delta) \quad \forall j \in \{1, \cdots, N_z\}, \end{aligned}$$

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$$\sum_{\gamma=h}^{H^c} I_j(\gamma) = U_j \quad \forall j\{1,\cdots,N_z\}, \gamma \in \{h,\cdots,H^c\}$$
$$\sum_{\gamma=h}^{\gamma+U_j-1} I_{j\gamma} \geq U_j y_j(\gamma),\ \forall \gamma \leq H^c - U_j + 1$$
$$y_j(\gamma) - z_j(\gamma) = I_j(\gamma) - I_j(\gamma-1),$$
$$\forall \gamma \in \{h,\cdots,H^c\} \quad \forall j\{1,\cdots,N_z\},$$
$$y_j(\gamma) + z_j(\gamma) \leq 1 \quad \forall j \in \{1,\ldots,N_z\}, \gamma \in \{h,\ldots,H^c\} \quad (14)$$

where $\mathcal{G}_j^h = [g_j(h),\ldots,g_j(H^P)]$. The problem in (15) has the following challenges:

- *(i)* The problem is a mixed integer linear program with spatial and temporal constraints which work on different time-scales.
- *(ii)* Designing the MPC controller is challenging due to time-coupled component dynamics of the zones and leads to scalability issues.
- *(iii)* Flexibility is required in RTM which works on a fast time-scales, thereby requiring algorithms that can compute the flexibility in good time.

Our objective is to propose a scalable solution technique for aggregating flexibility from different building zones to maximize the rewards while meeting user defined flexibility slots. Solving it with centralized approach for large scale building is computationally intractable problem. In what follows we proposed a hierarchical approach for solving the flexibility aggregation problem in buildings that is scalable for large number of zones and can meet user defined temporal and spatial constraints.

III. Contract Definitions

The zones publish their baseline contracts based on forecasts on heating loads, weather, occupancy, and other aspects solving the MPC in (5). This is the optimal energy to be consumed by each zone. The base-line contracts are aggregated by the building owner and the total flexibility availability is computed off-line. The building owner publishes this information in the RTM, *a priori*. This is received by the aggregator who modulates it based on utility triggers. The contracts are defined to provide scalability and for reliable operation. We discuss the contracts between different entities in this section.

A. Aggregator to Building Owner Contract

The aggregator announces rewards and time slots in which flexibility is required. The reward for upward and downward flexibility for the building is given by the rewards $\overline{\xi}$ and $\underline{\xi}$ as:

$$\overline{\xi}(P_T(h), P_T^u(h)) \triangleq \overline{\alpha}(h) \times (P_T^u(h) - P_T(h)),$$
$$\underline{\xi}(P_T(h), P_T^l(h)) \triangleq \underline{\alpha}(h) \times (P_T(h) - P_T^l(h)),$$

where $\overline{\alpha}$ and $\underline{\alpha}$ are the time-varying upward and downward flexibility cost that is modulated by the aggregator. In addition, the contract defines the time-period of the contract and power trajectory for the building denoted by the tuple $\{t_{sc}, t_{ec}, \underline{\xi}(h), \overline{\xi}(h), P_T(h)\} \quad \forall h \in \{t_{sc}, t_{sc}+\delta, \ldots, t_{ec}\}$. Here $P_T(h)$ is the power profile demanded for meeting grid requirements e.g., peak-demand reduction or even ancillary services request. The building owner needs to command the sum of cooling demands from different zones, i.e., G to meet the power profile.

B. Building Owners to Zones

On obtaining the aggregator contract, the building owner publishes the rewards that are proportional to the ones received from the aggregator. Upward and downward rewards are calculated as

$$\overline{\Phi}(h)(g(h), g^u(h)) \triangleq P_T(g^u(h) - g(h)),$$
$$\underline{\Phi}(h)(g(h), g^l(h)) \triangleq P_T(g(h) - g^l(h)).$$

In addition, the building owner publishes the time-slots in which the flexibility is required using the power profile information $P_T(h)$ set by the aggregator. Here $\overline{\Phi}$ and $\underline{\Phi}$ are modulated by the building owner to match the power profile $P_T(h)$ provided by the aggregator.

C. Zone to Building Owner Contract Definition

The user contract defines the spatial and temporal preferences required for aggregating flexibility from the buildings to grid and is defined by upward and downward spatial flexibility plus the number of slots committed by the user U_j and temporal preferences to give the flexibility in continuous or dispersed slots, i.e., $\Gamma = \{1, 0\}$, where '1' denotes the flexibility provision in continuous slots and '0' otherwise. Therefore, the user contract is defined using the tuple $\{U_j, \Gamma, g^l(h), g^h(h)\}$.

D. Scalable Flexible Aggregation Using Contracts

To aggregate flexibility with user defined contracts and RTM having both spatial and temporal constraints the optimization model in (15) has to be solved. As pointed out earlier solving the problem with numerous zone is a computationally intensive and methods to simplify the flexibility aggregation are required. We propose a hierarchical solution technique that decomposes the problem into two steps. They are: *(i)* flexibility computation, and *(ii)* provisioning user constraints. In the first step, the zones in a decentralized fashion solve a MPC to compute the base-line contract plus upward and downward flexibility. In the second step, the zone contracts are used by the building management system to provision the time-slots. These computations require user preferences and this is provided by the zone contracts. However, one can see that the temporal and spatial constraints are completely decoupled and equation (5) computes the flexibility that can be provisioned in each zone. The upward and downward flexibility can be computed by introducing a tracking term modelling the temperature bounds and the flexibility can be computed from each zone. Once the flexibility is computed, the second step is to include

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user preferences and this is done by solving the following optimization problem:

$$
\begin{aligned}
\min_{I_{jh}, y_{jh}, z_{jh}} \; & - \sum_{\gamma=h}^{H^c} max(0, \overline{\mathcal{R}}(\gamma)\overline{\Phi}(g_j(\gamma), g^u(\gamma))) I_j(\gamma) \\
& \qquad - \sum_{\gamma=h}^{H^c} max(0, \underline{\mathcal{R}}(\gamma)\underline{\Phi}(g_j(\gamma), g^l \gamma))) I_j(\gamma) \\
& - \sum_{\gamma=h}^{H^c} max(0, \overline{\mathcal{R}}(\gamma)\overline{\Phi}(g_j(\gamma), g^u(\gamma))) I_j(\gamma) \\
& \sum_{\gamma=h}^{H^c} I_j(\gamma) = U_j \quad \forall j\{1, \cdots, N_z\}, \gamma \in \{h, \cdots, H^c\} \\
& \sum_{\gamma=h}^{\gamma+U_j-1} I_{j\gamma} \geq U_j y_j(\gamma), \;\; \forall \gamma \leq H^c - U_j + 1 \\
& y_j(\gamma) - z_j(\gamma) = I_j(\gamma) - I_j(\gamma - 1), \\
& \qquad \forall \gamma \in \{h, \cdots, H^c\} \quad \forall j\{1, \cdots, N_z\}, \\
& y_j(\gamma) + z_j(\gamma) \leq 1 \quad \forall j \in \{1, \ldots, N_z\}, \gamma \in \{h, \ldots, H^c\}
\end{aligned} \tag{15}
$$

The problem in (15) is an integer optimization problem and can be solved to schedule the flexibility slots. As against solving a multiple time-horizon problem for the MPC, we solve a single-instance of the integer programming problem. This provides significant computation simplicity leading to scalable aggregation of flexibility from buildings.

E. Proposed Flexibility Contract Algorithm

The various steps involved in contracting flexibility is shown in Fig. 2. First, the utility negotiates energy prices in Day-Ahead Market (DAM) and publishes the market clearing prices which denote the energy per unit cost when demand and supply are equal. However, due to uncertain events such as sudden fluctuating load or renewable generation the supply and demand may not be matched for a specific time-period leading load imbalances. The utility sensing such situations sends triggers to the aggregators to publish their flexibility bids by specifying the contracts. Then the rewards are modulated by the utility based on the grid conditions.

The aggregator upon receiving the triggers sends flexibility requests to the buildings $\mathcal{B} = \{B_1 \cdots B_n\}$ connected to it and interfaces to the building using the contracts. For simplicity, we consider the case of a single building in our study. The BEMS of each $\mathcal{B}_i$ receives the demand response signals from the aggregator and then requests the individual zones in building $\mathcal{B}_i$ to send flexibility and the time preferences for providing it. The building owner of each $\mathcal{B}_i$ based on the triggers request individual zones to send their flexibility and base-line consumption along with time preferences. To compute the flexibility, the zones solve (5) in a decentralized fashion and transmit the base-line and flexibility to the BEMS. The decentralized requests are bundled and transmitted to the aggregator. The base-line, upward and downward flexibility are published based on

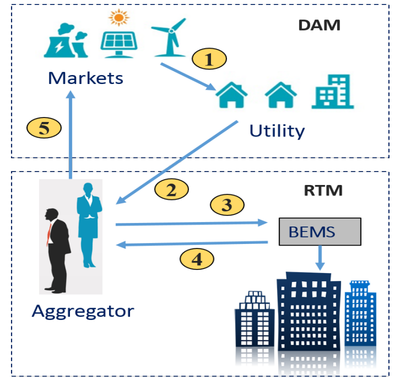

Fig. 2. Dynamic Flexibility Contract Scheme

zone temporal constraints. The aggregator publishes the bids in real-time market (RTM).

IV. Results

The proposed scalable contract based approach is illustrated using simulations on buildings with different scales. The zone dynamics are obtained from measurements taken from a test-bed S1B1 building housing the School of Electrical and Electronics Engineering, Nanyang Technological University, Singapore. The first set of simulations shows the study for 5 zones with occupant specified flexibility and then simulation analysis for 200 zones is presented.

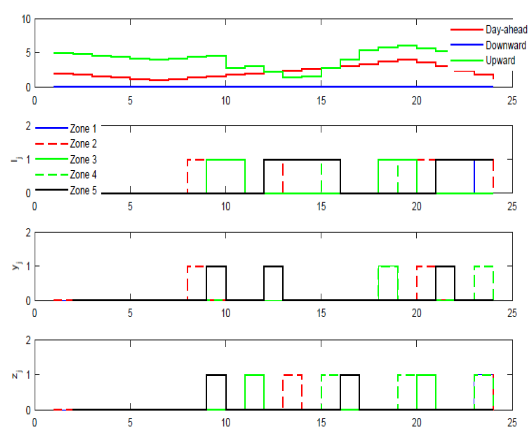

Fig. 3. (a) Per-unit energy rate (day-ahead and RTM), (b) Slots committed I_j, (c) decision variable y_j, (d) decision variable z_j

A. Case Study: 5 Zones

The simulation case-study consists of 5 zones whose model is identified with the data-set obtained from the test-bed. The use-defined comfort band of [24, 28] was used in our simulations and a sampling time of 15 minutes was used for control. In our contract, the number of time-slots committed by each zone are $U_j = [2\ 6\ 4\ 4\ 8]$. The variations in day-ahead prices and real-time prices are shown in Fig. 3(a). Since we consider cooling, only upward flexibility is rewarded for the considered case-study and the downward

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flexibility is equal to the day-ahead prices. The number of committed slots, the start of flexibility and end of flexibility is shown with binary decision variables in Fig. 3(b)-Fig.3(d). One can see that the proposed scheme schedules the flexibility based on user-defined slots.

The temperature profiles of five zones, base-line power computed from MPC, and the flexible power is shown in Fig 4. The temperature profile shows that the zone temperature is maintained within user-defined comfort bands. The deviation from the base-line and the base-line power in kW are shown in Fig. 4(b) and 4(c), respectively. One can see that the flexible power provided by zone during different time-slots and they can be aggregated by considering the user-defined comfort margins. The results demonstrate that the proposed method can be used for aggregating flexibility with user-define comfort margins and flexibility slots from zones in commercial buildings. Furthermore, the contract based approach enables market participation of zones for providing flexibility to the grid. Since user can decide the time-slots, this enables user participation in flexibility programs.

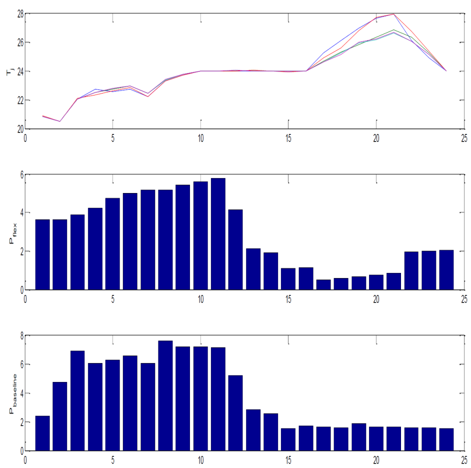

Fig. 4. (a) Temperature variations in 5 zones, (b) Flexible Power, (c) Baseline Power

B. Scalability

To study the scalability of the proposed method, we simulated the proposed approach for 200 zones. Due to decentralization of contract, we could compute the flexibility and schedules with an average time of 25 Seconds over 10 iterations. On the other hand, the centralized optimization methods wherein both the scheduling and flexibility computation are done at centralized level cannot scale beyond 50 zones. The computation of grid level flexibility is in the order of few mil-Seconds. Scheduling works on large time-scales and considering that only 25 Seconds are used for computation, therefore, the method provides good scalability. This makes the approach suitable for aggregating HVAC flexibility on fast-time scales.

V. CONCLUSIONS

This investigation presented a contract based approach for aggregating flexibility from multi-zone commercial buildings considering user-defined time-slots and comfort margins. Further, it enabled market participation of individual zones for providing flexibility to the grid on receiving triggers from utility. The flexibility are bundled from zone level and send to the aggregator who bundles it and sells it to the grid. The contracts for bidding flexibility from zones to building owner, aggregator, and utility are described. We show that the model for providing flexibility is mixed integer linear program which is difficult to solve due to complex zone thermal dynamics. To solve this problem, we propose a distributed optimization approach which provides scalability and performance. Simulation results for 200 zones and deployment for 5 zones are shown to illustrate our method. Extending the flexibility concept for providing ancillary service to the grid is the future course of investigation.

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