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THE IMPORTANCE OF PROPER SCHEDULING OF ENERGY EQUIPMENT IN COMBINED HEAT AND POWER PLANTS FOR BUILDINGS: A CASE STUDY

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ABSTRACT
There is increasing interest in using Combined Heat and Power (CHP) systems to supply the energy needs in commercial/institutional buildings. However, due to the large diurnal and seasonal variability in building thermal and electric loads, such systems in buildings (BCHP) require more careful and sophisticated operation as compared to those in industrial CHP. Operating such systems consists of two separate issues: (i) equipment scheduling which involves determining which of the numerous equipment combinations to operate, i.e., is concerned with starting or stopping prime movers, boilers and chillers; and (ii) the second and lower level type of control, called supervisory control, which involves determining the optimal values of the control parameters (such as loading of primemovers, boilers and chillers) under a specific combination of equipment schedule. This paper is concerned with both these aspects, and presents case study results of a school under real-time electrical pricing (RTP) located in New York City, NY. A school has been selected for study because of its high diurnal and seasonal load variability. The approach first involved simulating the buildings using a detailed building energy simulation program to obtain hourly electrical and thermal loads which were then used to size the BCHP system components. Subsequently, a certain number of days in the year were identified, and simulation runs were performed for optimal scheduling control as well as for all the feasible (but non-optimal) equipment combinations. The energy and cost implications of operating the BCHP system in a non-optimal manner under various scheduling combinations are presented and discussed.

KEYWORDS
Combined heat and power, cost optimization, optimal scheduling control, cost penalties of non-optimal control, CHP for schools

BACKGROUND
Combined Heat and Power (CHP) components and systems are described in several books and technical papers (for example, see Petchers, 2003; ASHRAE, 2004). Such systems meant for commercial/institutional buildings (BCHP) involve multiple prime movers, chillers and boilers and require more careful and sophisticated equipment scheduling and control methods as compared to those in industrial CHP, due to the large variability in thermal and electric loads as well as the equipment scheduling issue. Research into methods to optimize energy consumption or cost of operation of building systems is not new (refer to review articles by Henze, 2003 or Wang and Ma, 2008). However, many of the efforts specifically address optimization of one or two specific building systems (e.g., thermal storage, or start/stop of chillers and/or boiler systems). Currently, little optimization of the interactions among systems is done in buildings. Attempts in practice to optimize operations usually involve applying rules of thumb regarding when to turn on boilers or chillers, how to reset set points, and other heuristic actions. There is little or no analytic basis for control of scheduling and interactions in real time. Shedding of loads in response to day-ahead or hour-ahead notifications of need from utilities works well in practice, but as electric rate structures become increasingly time variant, real-time control of scheduling and system interactions will become essential for cost-effective operation. Heuristic control normally used by plant operators often results in off-optimal operation due to the numerous control options available to them as well as due to dynamic, time-varying rate structures and relative changes in gas and electricity prices. Though reliable estimates are lacking in the technical literature, the consensus is that 5-15% of cost savings can be realized if these multiple-equipment BCHP plants were operated more rationally and optimally.

There are a few computer software programs, which have been developed by federal agencies (for example, Fisher and Glazer, 2002) consultants and equipment companies for designing BCHP plants. Many of them use simple models of equipment and simplistic operating scenarios. Most of these programs are **design tools**, which are an add-on to existing programs such as DOE-2 (LBL, 1989) or adopt bin-type analysis methods to determine type and size of BCHP systems to be used during the design and selection process. There have been several papers and books, which describe heuristic practices of operating cooling plants (Kelly and Chan, 1999; Braun et al., 1989; ASHRAE, 2007 to name a few), hybrid cooling plants (Koeppel et al., 1995; Siemens, 2004; Braun, 2006) and even co-generation plants (for example, Honeywell, 2006; Petchers, 2005). However, there has been no systematic guidance on how to operate BCHP plants, and a proper understanding of the cost penalties associated with operating them in a non-optimal manner is lacking. A recent research study by Maor and Reddy (2008) has been completed which addresses this issue. A comprehensive literature review is also provided therein.

OBJECTIVES AND SCOPE

There are two distinct aspects in the proper operation of CHP plants: (i) equipment scheduling which entails determining which of the numerous equipment combinations to operate, i.e., is concerned with starting or stopping prime movers, boilers and chillers; and (ii) a second and lower level type of control called supervisory control which involves determining the optimal values of the control parameters (such as loading of primemovers, boilers and chillers) under a specific combination of equipment schedule. Most of the work to date in the heating, ventilating, air-conditioning and refrigeration (HVAC&R) literature (specifically chiller plants) focused on the lower level objective since the studies were concerned with simpler systems where the number of possible equipment combinations is relatively few. Also, one needs to differentiate between two terms: **optimal and near-optimal,** which are used differently by different professionals. One manner of differentiating these is to view the latter as a simplification of the former in terms of the modeling equations describing the performance of the various equipment, the methods of framing and solving the optimization function, and whether the problem is treated as a static or a dynamic problem (i.e., treating the problem on an hourly basis or over a planning horizon which could be several hours in a day or a whole month as well). A second viewpoint is to consider near-optimal as synonymous with simplified and heuristic strategies which are close to the optimum one but are much simpler to implement in actual practice.

Near-optimal scheduling control has been defined differently in the current paper. **Optimal scheduling control** is defined as one where the BCHP operators are able to instantaneously switch on or shut down needed equipment at the start of each time period (in this study, one hour), and operated optimally during that period so as to minimize energy cost while meeting the required loads. Practical considerations (as described and treated by Jiang and Reddy, 2007) related to such an operation, such as time delay in bringing equipment online, start-up transient spikes in energy use,.. have been overlooked. From a practical operational viewpoint, however, BCHP operators are averse to switching equipment on and off over the planning horizon, and they would prefer to select a particular set of BCHP equipment to startup at the beginning of the planning horizon and keep this set operational till the end with, however, the ability to control the individual already operating equipment at smaller time steps (say, each hour) in an optimal manner. While optimal is one where both the equipment scheduling and control can be done optimally each hour, **near-optimal** in this research is defined as an operational strategy where one cannot change the equipment scheduling during the planning horizon, but whichever equipment is operating can be controlled so as to result in minimum operating cost. Thus, there will be as many near-optimal solutions as there are feasible combinations during the selected day. A quantity called **CPR (cost penalty ratio)** has been defined as the ratio of the near-optimal to the optimal costs of operating the BCHP system over the diurnal time horizon, and the magnitude and variation of this quantity with building type, location and price signal was studied in a research study (Maor and Reddy, 2008). The objective of this paper is to report on research results from that study as they pertain to proper scheduling of equipment in BCHP systems for a school building which has been selected because of its high diurnal and seasonal load variability

SYSTEM MODELS AND SIMPLIFYING ASSUMPTIONS

The integration of the lower-level continuous control plant optimization capability into the high-level cost optimization is computationally demanding when the system has many components. Some strategies can be used to weed out combinations by imposing some physical constraints from practical experience (Olson, 1988). A good approach, which works well for multi-speed cooling tower, is to treat the relative flows as continuous control variables and to select the discrete relative flow that is closest to that determined with continuous optimization (ASHRAE, 2007). In fact, with many current designs, individual pumps are physically coupled with chillers and it is impossible to operate greater or fewer pumps than the number of chillers operating. Thus, such a practical constraint reduces the number of combinations greatly.

Figure 1 is a generic schematic of how the important subsystems of a BCHP system (namely, primemovers, vapor compression chillers, absorption chillers and boilers) are often coupled to serve the building loads (namely, the non-cooling electric load, the cooling thermal load, and the heating thermal load). The figure also indicates the nomenclature adopted for the various equipment models described below. Note that we exclude the option of electricity sell-back to the utility which is consistent with how most BCHP plants are operated to-date.

Part-load electrical efficiency of reciprocating engines can be modeled by polynomial functions (Hudson, 2005), from which the amount of natural gas heat input (E_Gen) and the amount of waste heat which can be recovered from the primemover under part-load conditions (H_Gen) can be deduced (Reddy and Maor, 2009). Part-load performance of vapor compression and absorption chillers can also be modeled using polynomial models (Braun, 2006) while DOE-2 simulation model (LBL, 1989) provides polynomial models for boiler performance. We have intentionally chosen not to incorporate cooling tower-specific models which are well-known (Braun, 2006). This requires sub-optimization and given the scope of this research, we have simply assumed that the cooling tower operates at its rated performance throughout. This assumption results in no more than 2-3% error in estimating diurnal costs during the optimization. Finally, models for O&M costs for primemovers, heating and cooling equipment are fully described in Maor and Reddy (2008).

The simplifying assumptions made during the modeling, simulation and optimization are:

i. The optimization is based on operating cost only. Issues related to environmental benefits/penalties of BCHP plants have been excluded.
ii. The building does not have net metering, i.e., electric utility buyback is not an option.
iii. Simulation is quasi-static, i.e., transient effects associated with power surge and extra energy consumed due to time delay in equipment start-up and shut-down are neglected (consistent with Braun, 2006).
iv. Non-chiller electricity, cooling thermal and heating thermal loads of the building are known without uncertainty; i.e., they are deterministic.
v. Electricity and gas prices are known without uncertainty.
vi. Simulation time step or time interval is assumed to be one hour with the simulation time horizon for each scenario selected on a case by case basis.
vii. Component models have no uncertainty.
viii. Chilled water supply set points are constant at 44^0F (Braun, 2006).
ix. The chillers operate on a primary/secondary configuration on the chilled water side (i.e, all chillers operate under the same evaporator inlet water temperature) but have separate individual cooling tower loops on the condenser side.
x. Each chiller has its own dedicated condenser water pump and evaporator water pump with constant flow and on/off control.
xi. Each chiller has its own dedicated cooling tower with variable fan control.
xii. The cooling tower fan power is not included in the optimization. The fan control is assumed such that it maintains the rated value of the condenser inlet water temperature throughout the year.
xiii. Pump and/or fan electricity for either the secondary chilled water loop or the air-handler loop on the building side are not considered in the optimization.
xiv. The boilers and heat recovery units have common supply and return headers though each unit has its own dedicated water pump with constant flow and on/off control.
xv. The supply hot water header feeds the absorption chiller and the sensible heating of the building via dedicated constant speed pumps with constant flow and on/off control.
xvi. Domestic hot water pumping electricity is not included.
xvii. The optimization does consider the possibility of hot water and chilled water being dumped if necessary, though in actual operation, BCHP operators are very unlikely to do so.

OPTIMIZATION UNDER RTP RATES

This study is limited to the case of real time pricing (RTP) of electricity rate structure which is becoming increasingly prevalent. Note that RTP is characterized by a variable unit cost of electric energy but does not include a demand charge. Rather than perform a mixed integer programming optimization, it is simpler to perform individual optimizations for each equipment combination, and thereby deduce the optimal system combination to operate. In that manner, one is able to evaluate cost differences between the various combinations. Figure 1 provides a simple manner of visualizing the various energy flows between the primary BCHP equipment.

<u>(a) Case 1. Static or single period optimization without demand charge (1 hour)</u>

The static optimization case *without utility sell-back* involves optimizing the operating cost of the BCHP system for each time step, i.e. each hour, while it meets the building loads: the non-cooling electric load (E_{Bldg}), the thermal cooling load (Q_c) and the building thermal heating load (Q_h). The cost components only include steady state hourly energy costs for electricity and gas. So, the quantity to be minimized, J, is the total cost of energy consumption, summed over all components that are operating plus the equipment operation and maintenance (O&M) costs. The energy consumption for each of the *k* components is a function of the component's characteristics and is dependent upon the controlled variables as given by the set of equipment modeling equations described earlier.

The **objective function** to be optimized for a particular time step (or hour) and for a specific BCHP system combination:

$$\tilde{J} = \min\{J\} = \min\{J_1 + J_2 + J_3\} \qquad (1)$$

where

- the cost associated with gas use is

$$J_1 = (G_{Gen} + G_{BP}).C_g$$

- the cost associated with electric use is

$$J_2 = E_{Purchase}.C_e \qquad (2)$$

- the operation and maintenance cost is

$$J_3 = M_{OM}$$

subject to the **inequality constraints** that the building loads must be met (i.e., functional constraints): (3)

- building thermal cooling load

$$Q_{AC} + Q_{VC} \geq Q_c$$

- building thermal heating load

$$Q_{BP} + H_{Gen} - H_{AC} \geq Q_h$$

- building non-cooling electric load

$$(E_{Purchase} + E_{Gen} - E_{VC} - E_p) \geq E_{Bldg}$$

and subject to boundary or **range constraints** that (4)

- the primemover part load ratio

$$0.30 \le x_{Gen} \le 1.0$$

- the vapor compression chiller part load ratio

$$0.15 \le x_{VC} \le 1.0$$

- the absorption chiller part load ratio

$$0.20 \le x_{AC} \le 1.0$$

- the boiler plant part load ratio

$$0.20 \le x_{BP} \le 1.0$$

Note that we have allowed for the possibility of dumping either thermal cooling or thermal heating energy. The decision variables are the four part load ratios (x_{AC}, x_{BP}, x_{Gen}, x_{VC}) whose respective values are to be determined which minimize the objective function J. If K is the number of BCHP system combinations, then the best BCHP combination among the K combinations is the one which has the lowest cost and is determined from:

$$\tilde{J}_{k^*} = \min\{J_k\} \text{ for } k \in [1...K] \quad (5)$$

where $\min\{J_k\}$ is given by eq. 1 for a specific system combination k, and k* is the index for the optimal BCHP combination. This is the **optimal solution** for the BCHP supervisory control problem within the simplifying modeling and simulation assumptions stated earlier. Note that not all possible BCHP system combinations may be feasible ones. Some of them will be such that the inequality constraints (given by eq. 3) cannot be met, and these combinations have to be discarded as potential solutions.

(b) Case 2. Dynamic or multi-period optimization without demand charge (time horizon of several hours during a day)

Multi-period optimization, in this instance, refers to the dynamic case where one wishes to determine the optimal scheduling and operation of the BCHP plant under pre-stipulated building load profiles and electric use price signals (without a demand charge) during a certain planning horizon or period of the day. Let t be the subscript denoting the hourly periods such that $t \in [1...T]$.

One can distinguish between two cases:

(i) Ideal or optimal operation where the BCHP plant equipment can be re-scheduled at the start of each hourly period and that the plant equipment is operated optimally at each of the T periods. The vector of optimal hourly scheduling control is:

$$\vec{J}_{k^*} = [\tilde{J}_{k^*,1}, \tilde{J}_{k^*,2}, ..., \tilde{J}_{k^*,t}, ..., \tilde{J}_{k^*,T}] \quad (6a)$$

where $\tilde{J}_{k^*,t}$ is found by simply solving eq. (5) separately for each time period.

The optimal cost of operating the BCHP over the time horizon is:

$$sum(J_{k^*}) = \sum_{t=1}^{T} J_{k^*,t} \quad (6b)$$

(ii) Near-optimal operation where, due to practical reasons discussed earlier, the BCHP operators would like to start a pre-selected combination of BCHP equipment at the beginning of the planning time horizon and keep that set operating throughout the T periods. Note that there is, however, the capability of controlling the part-load operation of the equipment that is already running at the start of each hourly time step so as to achieve optimal operation during that hour. In other words, x_{AC}, x_{BP}, x_{Gen}, x_{VC} can be viewed as being controlled hourly. This case is represented mathematically for each feasible combination k:

$$sum(\tilde{J}_k) = \sum_{t=1}^{T} \min\{J_{k,t}\} \quad (7a)$$

The computational algorithm starts by first selecting a specific BCHP system combination k, and determining the minimum operational costs for each of the T hours of operation individually. The sum of these hourly costs yields the total cost of operating that specific combination k over the planning horizon. This is repeated for all the combinations (discarding the ones which are unfeasible). The feasible combination k' which has the lowest total cost over the planning horizon is the best near-optimal solution sought:

$$sum(\tilde{J}_{k'}) = \min\{sum(\tilde{J}_k) \text{ for } k \in [1...k]\} \quad (7b)$$

DATA GENERATION

A synthetic DOE 2.1 E building energy simulation model (LBL, 1989) was developed for the large 229,700 sqft high school facility designed to accommodate around 1,500 students (see Maor and Reddy, 2008 for more details). The location selected for the school is the NYC area, NY. The facility is a campus which comprises of the following areas (see Fig. 2 for a rendering of the whole campus): two three-story classroom wings; one two-story special classroom wing which includes library and special areas such as educational labs, computer classrooms etc.; two gymnasium wings to accommodate three gymnasiums; auditorium wing; cafeteria wing; central Utility Plant to accommodate chillers, boilers, pumps etc.; one story administration annex; and two-story common (link) section.

Minimum building envelope properties, systems efficiencies, etc. and operating schedules (lighting, occupancy, etc.) were used based mainly on data from ASHRAE 90.1-2004 (ASHRAE, 2004). A variety of secondary air systems used for the design, these systems includes Four Pipe Fan Coils (FPFC) for classrooms, Variable Air Volume (VAV) with reheat for the common areas and admin and Single Zone (SZ) for auditorium, gymnasiums and cafeteria. A summary of the BCHP equipment is given in Table 1. This scenario assumes that the BCHP systems part of the original design from 1999. The energy costs are based on Con-ED from 1999-2000 Service Classification No. 9: Rate I, with the gas price in 1999 taken to be $ 7.75 /MMBtu.

A single 590 kW natural gas reciprocating primemover was selected, the details of the selection process are given in Maor and Reddy (2008). The primary system also includes two water cooled, electric screw chillers 257 Ton each and one 110 Ton single stage absorption chiller yielding a total chilled water plant capacity of 624 Ton (520 Ton calculated peak cooling capacity). The hot water heating plant consists of two gas fired flexible water tube each with 5,600,000 Btu/h output and one heat recovery heat exchanger (from the prime mover) with heating capacity of 2,640,000 Btu/h resulting in a total installed heating capacity of 13,840,000 Btu/h (total calculated peak heating capacity is 9,666,000 Btu/h). Chiller operation has been restricted (as is common in school facilities) by assuming the chillers to be switched off during winter.

There are 36 several possible combinations of operating the various BCHP equipment (see Table 2). A single equipment can assume two states (on or off), while two identical equipment can assume three states: both on, one on, and both off. The fact that there are so many combinations is problematic for BCHP operators since starting the non-optimal combination can have a resulting cost penalty.

BUILDING LOAD PROFILES AND SELECTION OF DAYS

The building loads of interest are the whole-building thermal heating loads, thermal cooling loads and the non-cooling related electrical loads. The hourly values of these three loads in conjunction with the climatic data (such as ambient air dry-bulb temperature) are available from the building energy simulation program results.

The justification for adopting intelligent control of a BCHP system is bound to differ depending on the specific day selected for study. The relative and absolute behavior of the building loads and their diurnal variation as well as that of the RTP electric rates are bound to heavily influence our optimization results. It is obvious that optimization analysis for all 365 days per year would provide the most exhaustive evaluation but since we have a large number of combinations for each scenario the computing task will be very time consuming, and further, one would be hard pressed to draw meaningful underlying patterns from the large mass of simulation results. The intent is to identify days which will provide sufficient information to determine the rational of intelligent control for the CHP applied for this building. In order to cover a wide range of electrical cost, the following methodology was adopted to select a few days during the year during which to perform the CHP optimization (Maor and Reddy, 2008):

1. Determine an electrical price window for the prototype days based on average daily base electrical cost from RTP data. The corresponding frequency distribution was generated from which we infer that a range between 0.045 - 0.085 $/kWh would cover 90 % of the days per year.
2. Determine days with low and high cooling and heating loads. This is inferred from DOE 2.1 E building simulation results.
3. Match actual days from selected RTP data (from the price window selected in step 1) to day in the DOE .2 1 E model (from step 2). Also check the deviation in ambient temperature of the actual days and the TMY days assumed by the DOE 2.1 E simulation
4. Develop hour by hour price signal for the day selected by converting the hourly price signals from base price to customer price.

This approach involved selecting a few days based both on RTP price and loads. Ten days which capture a price range of electricity which is approximately 90 % of that of the year (0.045 $/ kWh and 0.085 $/kWh – base daily average price), during the three seasons (Winter, Summer, Fall), and under two load cooling and heating profiles for each season were identified (see Table 3). The electric loads (not shown in Figs. 3 and 4) vary from 150 – 550 kW from daytime to nighttime during weekdays and from 150 – 200 kW during weekends with no seasonal trend. On the other hand the thermal loads vary widely from season to season. Figures 3 and 4 depict the large variability in the cooling and heating thermal loads for the winter and summer days along with the RTP price signals. These diurnal profiles suggested that a 15 hr time horizon for each of the 10 days (from 7:00 am – 9:00 pm) would be appropriate.

SIMULATION AND DATA ANALYSIS

We have as many near-optimal solutions as there are feasible combinations during the selected day. The **CPR (cost penalty ratio)** is the ratio of the near-optimal operating cost to the optimal or minimum operating cost over the diurnal time horizon selected. Table 3 provides information on the number of possible combinations; for example, for Scenario 1 under FLHL-RTPH, there are 25 feasible combinations out of a possible 36. In addition, the table shows the operating of the BCHP plant under “ideal operation” (defined earlier), and also assembles overall summary statistics (min, median, and max values) of the CPR values for all scenarios and selected days.

The cost of operating the BCHP plant during the 15 hr time horizon varies greatly across the 10 selected days. It is a minimum ($248) in winter under low RTP rates (WLH-RTL) and reaches a high of $1,476 during summer (SLH-RTPH). Also, the number of feasible combinations for the 10 days is from 15-27 (except for SLH-RTPH when it is 5), which is a large number of choices for the BCHP operator.

We find large variability in the CPR values for the 10 selected days (see Table 3 and Fig.5). The box and whisker plots of Figure 6 provide a clearer summary of the data spread across selected days. The span of the boxes represent the inter-quartile range, i.e. the CPR values of the 25-50 percentile range of the near-optimal solutions. The length of the whiskers is indicative of the differences in CPR values between the best and the worst near-optimal solution. Figure 7 is also another manner of graphically representing the variation in the CPR values across combination types which clearly indicates the effect of operating different individual pieces of equipment. We note that possible range of variation of the CPR values is large. The maximum values are in the range of 1.39 – 2.84, while the median values are from 1.08 during summer (when there are only 5 feasible combinations) to 1.95 during winter (WLH-RTPL). Hence there is great risk for large cost penalties since it is more likely that the operator will select an non-ideal combination. What is noteworthy, however, is that the minimum values of the CPR variable are close to unity indicating that there is one operating strategy where the near-optimal operation will be as good as the optimal one.

We find that there is no clear single near-optimal combination that is best for all cases- look at the last two columns of Table 3. Generally, there is only one combination with CRP<1.05, and only 2-3 with CPR<1.10. Moreover, there is no clear indication of as to which combinations are the best near-optimal ones since they vary across the 10 selected days (see Table 3). These observations suggest that there is likely to be great benefit if a BCHP supervisory tool is present.

Finally, the effect of including the costs associated with operation and maintenance of the specific equipment being scheduled was found to have almost no effect on the near-optimal solutions. Though the total estimate of cost over the planning horizon is affected, it is by very little compared to the fuel cost of the primemovers and the boilers. Hence, O&M costs can be overlooked during the optimization for identifying optimal and near-optimal scheduling**.**

SUMMARY

The parametric simulations allowed us to quantify the magnitude and variability of the CPR values across the large school campus. This research revealed: (i) that a bad choice in equipment scheduling can have a major cost penalty, (ii) that these penalties are large, (iii) that there is generally one near-optimal combination with almost no cost penalty compared to the ideal operation, (iv) that these combinations vary across the seasonal days selected. The lack of clear or simple rules for near-optimal scheduling of BCHP systems and the fact that a cookbook approach is likely to lead to large cost penalties highlights the need to have a software tool for optimal scheduling and control of BCHP plants. Future extensions of this research would include the following: (i) Sensitivity to simplifying assumptions such as the cooling tower effect, (ii) effect of uncertainties of the building loads, (iii) refinements to objective function which could include environmental effects, electric network congestion to the utilities, (iv) sub-hourly time step of simulation, and (v) inclusion of dynamic effects such as start-stop penalties of equipment.

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NOMENCLATURE

C_e	unit energy cost of electricity use ($/kWh)
C_g	unit energy cost of natural gas ($/MMBtu)
CPR	cost penalty ratio
E_{Bldg}	non-cooling electric building load demand (kWh/hr)
E_{Gen}	actual electric power output of primemover (kWh/hr)
$E_{Purchase}$	amount of purchased electricity (kWh/hr)
E_p	parasitic electric use of the BCHP plant (pumps, fans, etc.) (kWh/hr)
E_{VC}	electricity consumed by the vapor compression chiller (kWh/hr)
G_{BP}	amount of natural gas heat consumed by the boiler plant (MMBtu/hr)
G_{Gen}	amount of natural gas heat consumed by the primemover (MMBtu/hr)
H_{AC}	heat supplied to the absorption chiller (MMBtu/hr)
H_{Gen}	total recovered waste heat from the primemover (MMBtu/hr)
J	objective cost function to be minimized
K	total number of combinations of equipment scheduling
k	index for equipment scheduling combination
k’	index for best near-optimal combination
k*	index for optimal equipment combination
M_{OM}	operation and maintenance costs of the BCHP equipment which are operated ($/hr)
Q_{AC}	amount of cooling supplied by the absorption chiller (MMBtu/hr)
Q_{BP}	amount of heating supplied by the boiler plant (MMBtu/hr)
Q_c	building thermal cooling load (MMBtu/hr)
Q_h	building heating load (MMBtu/hr)
Q_{VC}	amount of cooling supplied by the vapor compression chiller (MMBtu/hr)
T	total number of hourly periods over planning horizon
t	index for time period
x_{AC}	part load ratio of the absorption chiller
x_{BP}	part load ratio of the boiler plant
x_{Gen}	part load ratio of the primemover
x_{VC}	part load ratio of the vapor compression chiller

Subscripts

AC	absorption chiller
BP	boiler plant
Gen	generator or primemover
VC	vapor compression chiller

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Table 1. Specifics of the BCHP equipment

Equipment/ Description	Large school NYC, NY
Primemover- recips	**1 no**
Number of combinations	36
Electric price	RTP
Rated electric output kW	590
Rated net gas MMBtu/h	5.42
Rated electrical effy %	37.2
Hot water at 190F MMBtu/h	2.64
Dedicated aux pump power HP	10.0
Boiler plant	**2 nos.**
Rated heat output MMBtu/h	5.6
Natural gas use MMBtu/h	7.000
Thermal efficiency %	80.0 %
Boiler pump power HP	7.5
Cooling Plant	**2 nos +1 no.**
Vapor compression chiller capacity Tons	257
Electric power input kW	188.1
COP -	4.8
Chilled water pumps HP	15.0
Condenser water pumps HP	30.0
Cooling tower fan HP	15.0
Absorption Cool Tons	110
COP -	0.7
Chiller water Pump power HP	7.5
Condenser Water pump power HP	20.0
Cooling Tower fan HP	7.5

Both boilers and vapor compression chillers identical

Table 2. Various possible configurations and associated rated values (1- on; 0- off)

	Prime Movers	Boilers		Chillers		
Case	RE	SHHWB1	SHHWB2	WCCC1	WCCC2	WCHWAC1
1	1	1	1	1	1	1
2	1	1	1	1	1	0
3	1	1	1	1	0	1
4	1	1	1	1	0	0
5	1	1	1	0	0	1
6	1	1	1	0	0	0
7	1	1	0	1	1	1
8	1	1	0	1	1	0
9	1	1	0	1	0	1
10	1	1	0	1	0	0
11	1	1	0	0	0	1
12	1	1	0	0	0	0
13	1	0	0	1	1	1
14	1	0	0	1	1	0
15	1	0	0	1	0	1
16	1	0	0	1	0	0
17	1	0	0	0	0	1
18	1	0	0	0	0	0
19	0	1	1	1	1	1
20	0	1	1	1	1	0
21	0	1	1	1	0	1
22	0	1	1	1	0	0
23	0	1	1	0	0	1
24	0	1	1	0	0	0
25	0	1	0	1	1	1
26	0	1	0	1	1	0
27	0	1	0	1	0	1
28	0	1	0	1	0	0
29	0	1	0	0	0	1
30	0	1	0	0	0	0
31	0	0	0	1	1	1
32	0	0	0	1	1	0
33	0	0	0	1	0	1
34	0	0	0	1	0	0
35	0	0	0	0	0	1
36	0	0	0	0	0	0

Table 3. Description of the selected day types and analysis results with time horizon of 15 hours (7:00 am-9:00 pm)

Day	Season	Load	RTP Rate	Acronym	Feasible # of comb	Ideal operat. cost $/15h	Cost Penalty Ratio (CPR)			Combination # (see Table 3)	
							Min	Median	Max	CPR <1.05	1.05< CPR <1.1
1	Fall	High HL[1]	High	FLHL-RTPH	25	700	1.00	1.50	2.01	18:100000	11: 110001[2]
2	"	High HL	Low	FLHL-RTPL	20	747	1.11	1.34	1.59	-	16:100100
3	Winter	High HL	High	WLH-RTPH	17	796	1.01	1.43	2.07	6:111000	5: 111001
4	"	High HL	Low	WLH-RTPL	27	248	1.00	1.95	2.84	30: 010000	-
5	"	Low HL	High	WLL-RTPH	24	686	1.02	1.55	2.23	12: 110000	6: 111000 11:110001
6	"	Low HL	Low	WLL-RTPL	24	660	1.02	1.30	1.59	23:011001 29: 010001	28:010100
7	Summer	High CL	High	SLH-RTPH	5	1,476	1.00	1.08	1.36	7: 110111	1:11111 7:110111
8	"	High CL	Low	SLH-RTPL	27	283	1.00	1.88	2.53	30: 010000	-
9	"	Low CL	High	SLL-RTPL	15	927	1.02	1.35	1.85	15: 100101	9:110101
10	"	Low CL	Low	SLL-RTPL	15	978	1.00	1.19	1.33	15: 100101	9:110101

Note: 1) HL- heating load, CL- cooling load
2)110001 implies that reciprocating engine is on, one boiler on, both vapor compression chillers off, and absorption chiller on

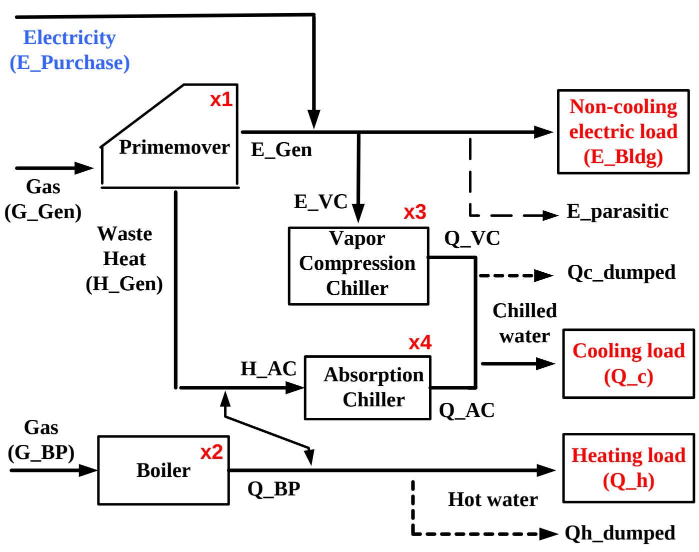


Figure 1. Generic schematic of the BCHP system depicting sub-system interactions and nomenclature used. The terms x1, x2, x3 and x4 represent the loading fractions of the primemover(s), boiler(s), vapor compression chiller(s) and the absorption chiller respectively.

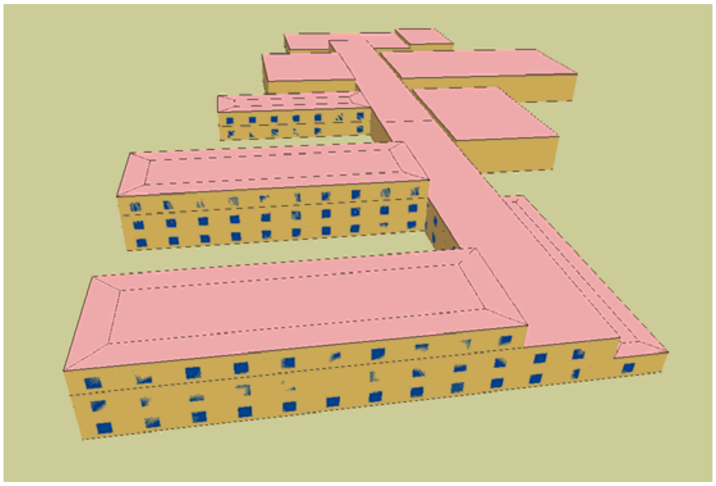
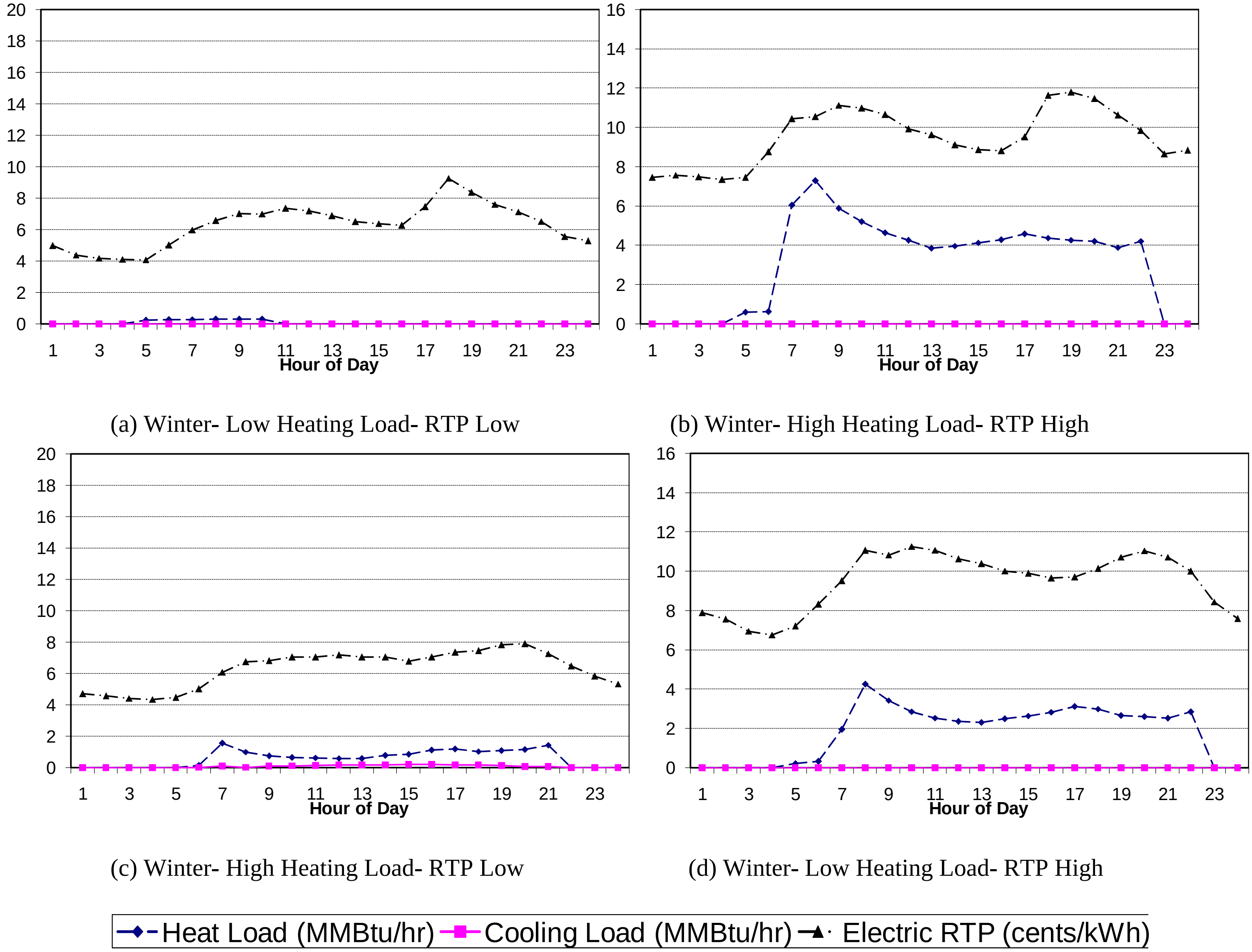


Figure 2. Rendering of the large school. campus



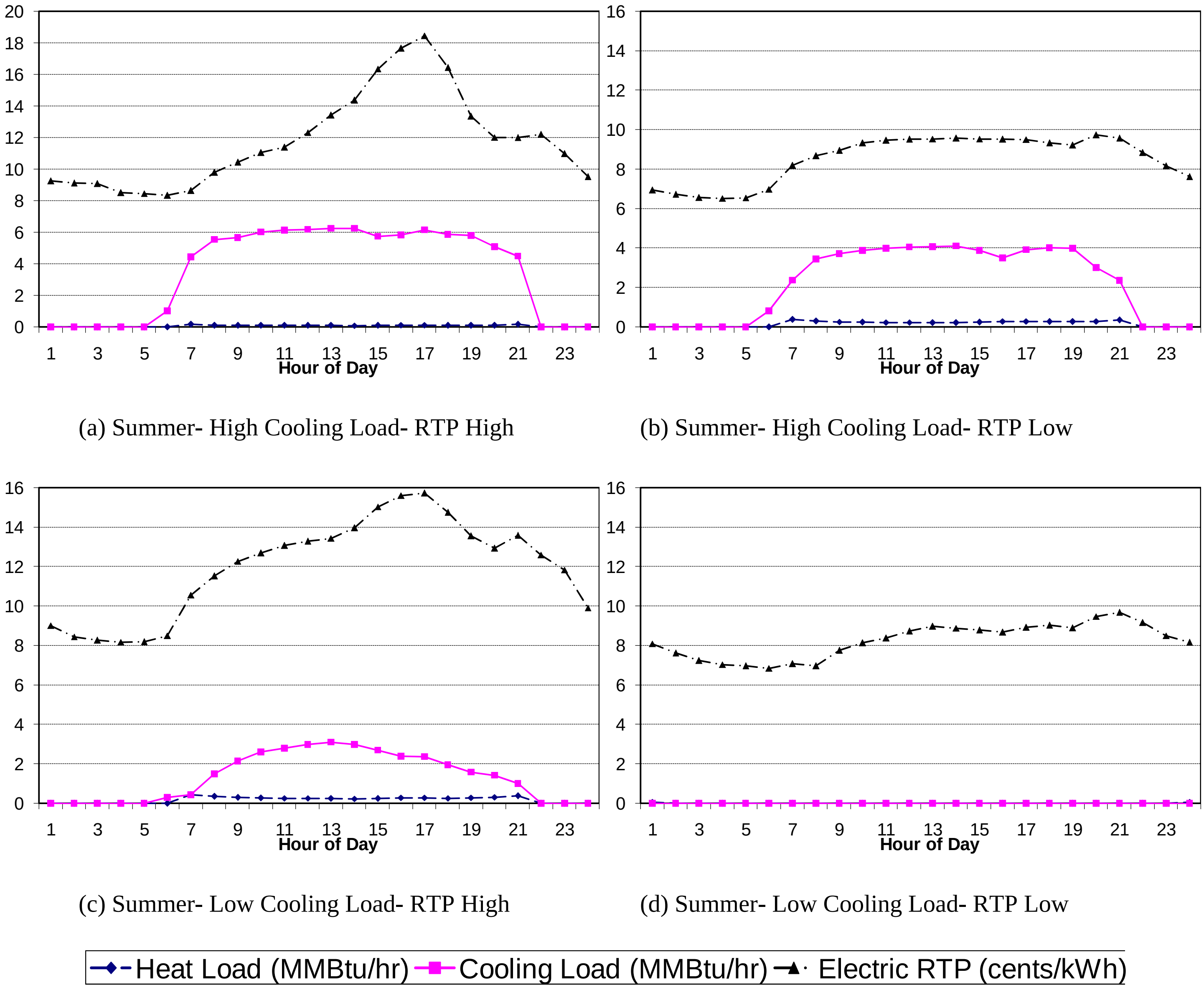
(a) Winter- Low Heating Load- RTP Low

(b) Winter- High Heating Load- RTP High

(c) Winter- High Heating Load- RTP Low

(d) Winter- Low Heating Load- RTP High

Figure 3. Diurnal profiles for the cooling and heating building loads and for the RTP electrical price signal for the four days during the <u>winter season</u> selected for simulation. Note that the cooling loads are close to zero for all four days. The optimization time horizon is 15 hr (from 7:00 – 21:00 hours).



(a) Summer- High Cooling Load- RTP High

(b) Summer- High Cooling Load- RTP Low

(c) Summer- Low Cooling Load- RTP High

(d) Summer- Low Cooling Load- RTP Low

Figure 4. Diurnal profiles for the cooling and heating building loads and for the RTP electrical price signal for the four days during the <u>summer season</u> selected for simulation. The optimization time horizon is 15 hr (from 7:00 – 21:00 hours).

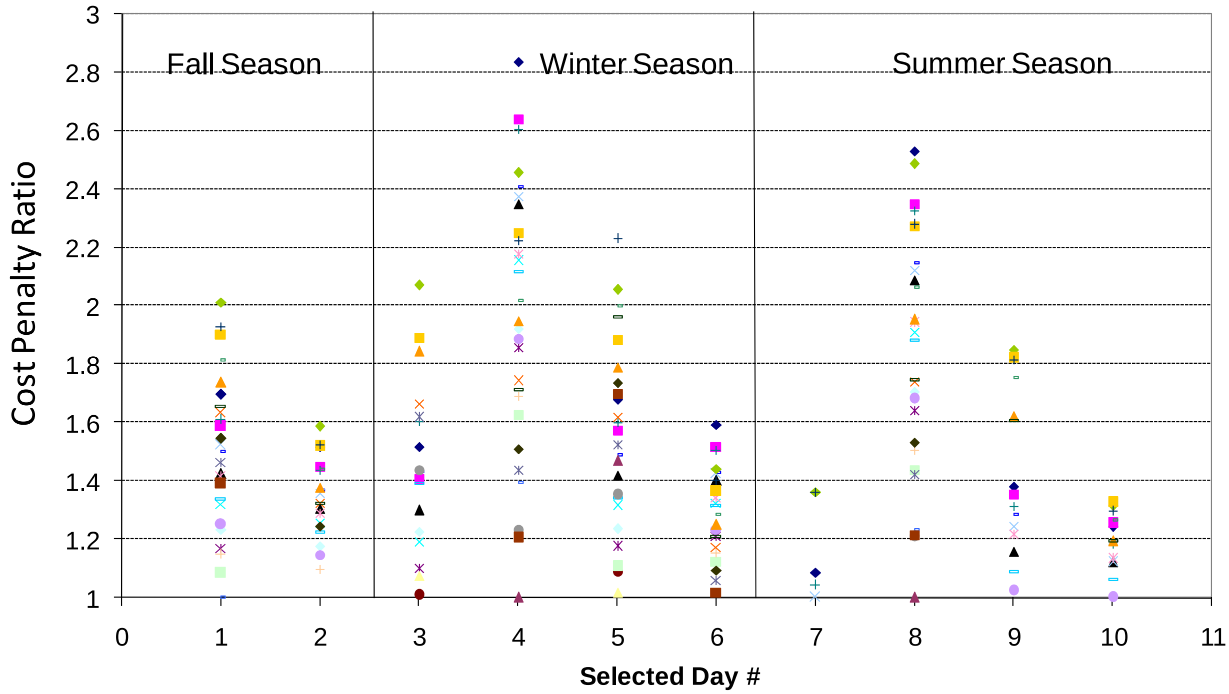


Figure 5. The spread in excess operating costs characterized by CPR during the 10 selected days over the 15 hour diurnal time horizon. Though there are 36 possible system combinations, only the results of the <u>feasible</u> system combinations are shown.

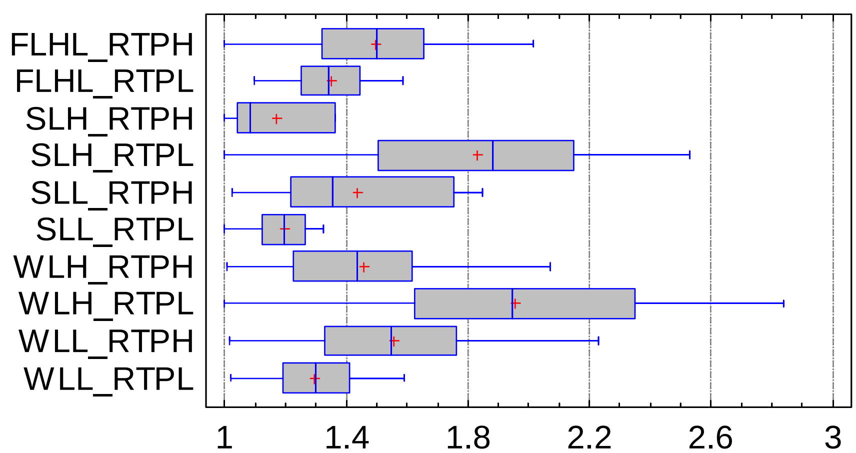
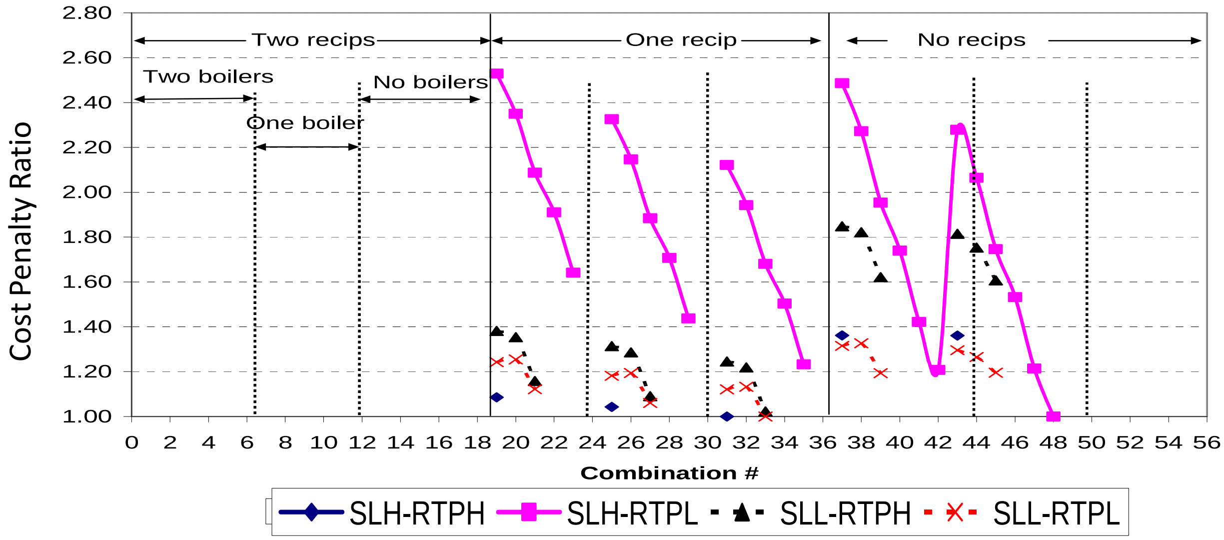
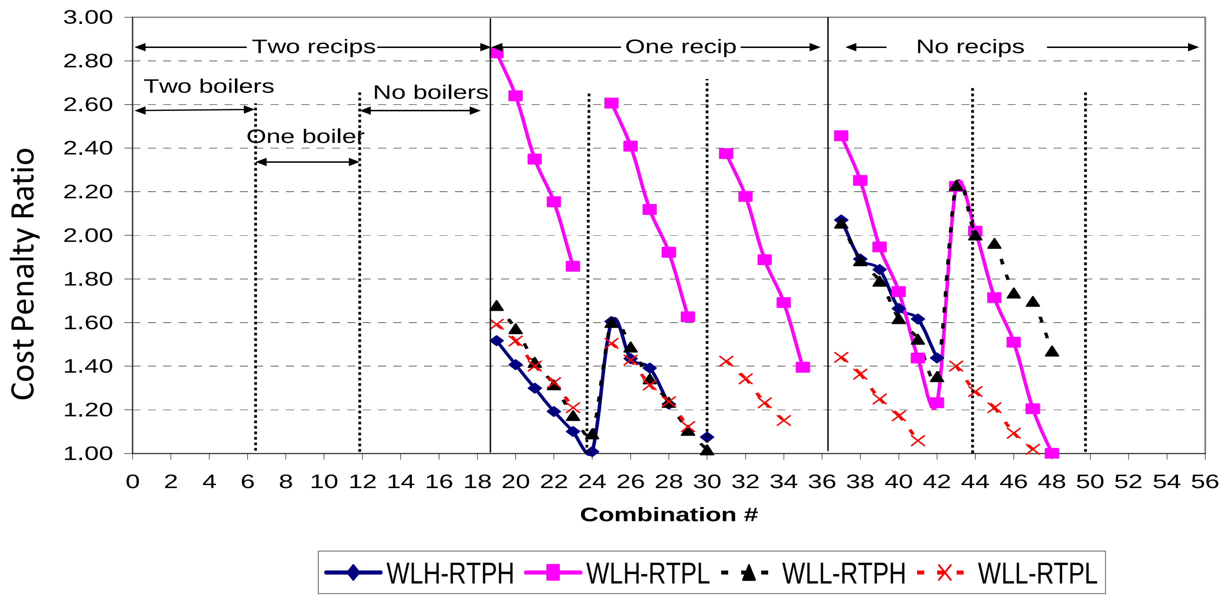


Figure 6. Box and whisker plots of the CPR values for the feasible combinations (see Table 3 for acronyms used).



(a) Summer days



(b) Winter days

Figure 7. Variation of the CPR values with system combination for the various winter and summer days