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Optimal operation of a hospital power plant

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Abstract

In this paper the operation of an Academic Hospital installation is evaluated by simulation and optimization on a yearly base. A mathematical model has been developed, which is based on energy balances of the installed components. Manufacturer specifications of the components are used for calculating the parameters. The model is formulated using vector equations. Advantages of this type of model formulations are presented. The tools used for optimization are custom developed back-tracking methods for calculating a good starting point and a SQP optimization tool for finding the optimum. Detailed control strategies are calculated for three types of optimization strategies simulated. The simulation results show the impact of the choice of a control strategy on the optimized operation. The results are also applicable for on-line setpoint optimization.

Keywords: Absorption chiller; Sequential quadratic programming; Combined heat and power

1. Introduction

It is no longer sufficient to design a system, which performs the desired task while observing constraints imposed by desired safety, economic output and other considerations. Due to the need to increase efficiency, it has become essential to optimize the process to minimize or maximize a chosen variable. This variable is known as the objective function (or *optimization criteria*) and may represent quantities like profit or energy [1]. Optimization of a system is often based on the profit or cost, though many other aspects, such as efficiency, energy, weight, size, etc. may also be optimized depending on the particular application. For example, a central heating plant can be designed for a desired amount of heat production. If a specific system is chosen, the various parameters such as operating temperature heat exchange area, water flow, etc. may be selected over a wide range of specifications [2]. All the designs may be acceptable because they satisfy the given requirements and constraints. It is necessary to seek an optimal design that will, for instance, consume the least amount of energy due to an environmental constraint or is most cost effective due to an economic constraint. An important optimization criterion of power plants is the efficiency of generating electricity. A small increase in efficiency can give a large increase in the profit. Nowadays, a lot of power plants use the produced heat for heating purpose, like the power plant at the Academic Hospital, Groningen. In this case of combined heat and power (CHP), the efficiency of generating electricity is not the only optimization criteria because the produced heat can also reduce the cost. Also present in the installation is an absorption chiller, which generates cooling from heat. So in summers, when cooling is needed, the produced heat of the power plant is not wasted but can be used for cooling purposes. Energy savings criteria are also very important in this case because the CHP part of the power plant is partly funded by the Dutch government. The main reasons for subsidizing CHPs are energy savings and CO_2 reduction. Due to the complexity of the power plant, it is very difficult to design an optimal operating strategy of the power plant. A computer model is therefore used.

A recent similar study on optimal operation has been done by Dentice [7]. The subject is also a complex thermal plant that is quit similar to the one presented in this paper. Although both models are based on the same principles, the model syntax are very different. Benefits of using the model syntax in this paper are presented in Section 3. Both studies use similar optimization solving techniques: start with the best point from a selection of trial points and refine the optimum. An important extension of the work of [7] is that in this paper the plant analysis and optimizations are performed on a yearly base. The papers of [3,6] deal with a more complex modeling of components. The thermal and

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Nomenclature

ACD	fraction of maximum capacity
c	controllable input variables of the model
CCD	fraction of maximum capacity of the mechanical chiller
CCD_{max}	maximum electrical power of the mechanical chiller (W)
dt	time step (s)
ElA	electricity needed at Academic Hospital (W)
Elbal	electricity balance (W)
ElC	electrical power of the mechanical chiller (W)
Epb	purchase price of electricity (€/J)
Eps	sale price of electricity (€/J)
EP	electricity profit (€/s)
Ekill	wasted useful heat of all gas engines (W)
G13	fraction of maximum capacity of gas engines 1–3
G45	fraction of maximum capacity of gas engines 4 and 5
gP	cost of supplied gas to boilers and all gas engines (€/s)
gpB	gas price of the boilers (€/m^3)
gpG	gas price of the gas engines (€/m^3)
g_{max13}	maximum gas supply to gas engines 1–3 (m^3/s)
g_{max45}	maximum gas supply to gas engines 4 and 5 (m^3/s)
h_{st}	enthalpy of steam at 8 bar (J/kg)
h_{cwa}	enthalpy of water at 12 °C (J/kg)
h_{hwa}	enthalpy of water at 100 °C (J/kg)
H	lower heating value (J/m^3)
i	non controllable input variables of the model
mlA	hot water needed at Academic Hospital (kg/s)
msA	steam needed at Academic Hospital (kg/s)
mgG	gas supply to all the gas engines (m^3/s)
mgB	gas supply to the boilers (m^3/s)
o	output variables of the model
P13	primary energy of gas supply of gas engines 1–3 (W)
P45	primary energy of gas supply of gas engines 4 and 5 (W)
QACDback	unused heat of the absorption chiller (W)
QcA	cooling needed at Academic Hospital (W)
QcB	cooling to ice storage (W)
QcBmax	maximum cooling content of the ice storage (J)
QcBsum	state-of-charge of the ice storage (J)
QCHbal	heat balance for switching on the absorption chiller (W)
QcSmax	maximum power of the absorption chiller (W)
QhA	heat needed for heating the Academic Hospital (W)
QBbal	heat balance for the boilers (W)
QB	demanded heat from the boilers (W)
QhSW	switch of supply heat to the absorption chiller (0 or 1)
QhACD	heat from gas engines to the absorption chiller (W)
QhCH	heat from gas engines for central heating of the Hospital (W)
Qprim	primary energy (W)
Totp	total profit (€/s)

Greek letters

η_{E13}	electric efficiency gas engines 1–3
η_{E45}	electric efficiency gas engines 4 and 5
η_{h13s}	thermal efficiency of heat from gas engines 1–3 to steam
η_{h13A}	thermal efficiency of heat from gas engines 1–3 to absorption chiller
η_{h13I}	thermal efficiency of heat from gas engines 1–3 to intercoolers
η_{h45A}	thermal efficiency of heat from gas engines 4 and 5 to absorption chiller
η_{h45I}	thermal efficiency of heat from gas engines 4 and 5 to intercoolers
η_{hK}	thermal efficiency boilers
η_{Epub}	public utility mean electric efficiency from primary energy
η_{cS}	thermal efficiency of absorption chiller (i.e. COP)
η_{cC}	thermal efficiency of mechanical chiller (i.e. COP)

electric efficiencies in [3,6] are dependent on temperatures. The thermal and electric efficiencies presented in this paper are modeled at a lower level and are dependent on the engine percentage loads. In [8], the electrical efficiency of a CHP is also successfully modeled by engine percentage loads. Other studies of optimal operation [8–10] deal with district heating systems using CHPs.

For modeling and optimization purposes, a system is needed that generates an optimized output from a certain input. This system contains a model and an optimization routine. The inputs of the model can be divided into a non-controllable input $i(t)$ and a controllable input $c(t)$. The output of the model is $o(t)$. The output of the model is used as input for the controller (optimization routine). The controller minimizes the impact of the non-controllable input $i(t)$ by manipulating c(t). Fig. 1 shows the principle of modeling and optimization. In order to develop an optimization program these steps are used for optimization:

1. design a model;
2. define non-controllable and controllable inputs and the output;

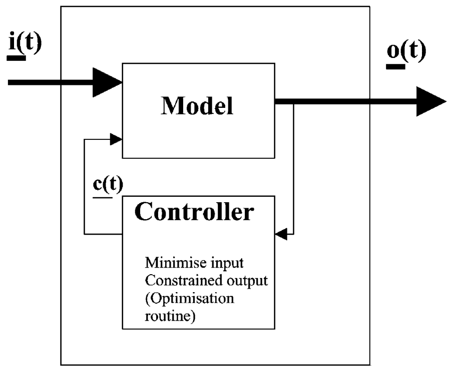

Fig. 1. The relation between model and optimization.

3. define constraints;
4. define optimization criteria;
5. build a numerical model;
6. select an appropriate time scale;
7. build a numerical optimization routine and calculate the optima.

2. The application

The central utility plant of the Academic Hospital Groningen has been selected as the subject for modeling and optimization. The installation meets the energy needs of the hospital. The installation is designed for producing domestic hot water and heating (30 MW), steam (8 MW), cooling (12 MW) and electricity (7.5 MW). Typical energy aspects of the installation in 1995 are: total heat consumption including the absorption chiller, 66 GWh; total electricity consumption, 27 GWh; gas consumption of the gas engines, 13,000,000 m^3; and gas consumption of the boilers, 3,000,000 m^3. The central power plant consists of three boilers, each with a capacity of 12 MW, five gas engines, each generating 2 MW electricity and 2.5 MW heat, one absorption chiller for generating 3 MW cooling from heat. Distributed over the hospital terrain are seven cooling units connected to the cooling circuit, each of which contains a mechanical chiller of 1.1 MW and a cool storage tank (TES) of 16 GJ. Fig. 2 shows the central power plant in detail (the seven cooling units are omitted in this figure).

3. Modeling and optimization

In this section the steps that are used for optimization are described. The model equations are based on a quasi-steady approach (the variables are approximate constant between two time steps) and contain scalar (normal letter type) and vector variables (bold letter) which contain values for this variable at each time step for a whole year. Compared with the model syntax of [7], this syntax has the next more practical benefits: (1) Time efficient computation, the vector-based model equations are identical to the equations programmed in MatLab [4]. Since MatLab is a vector oriented

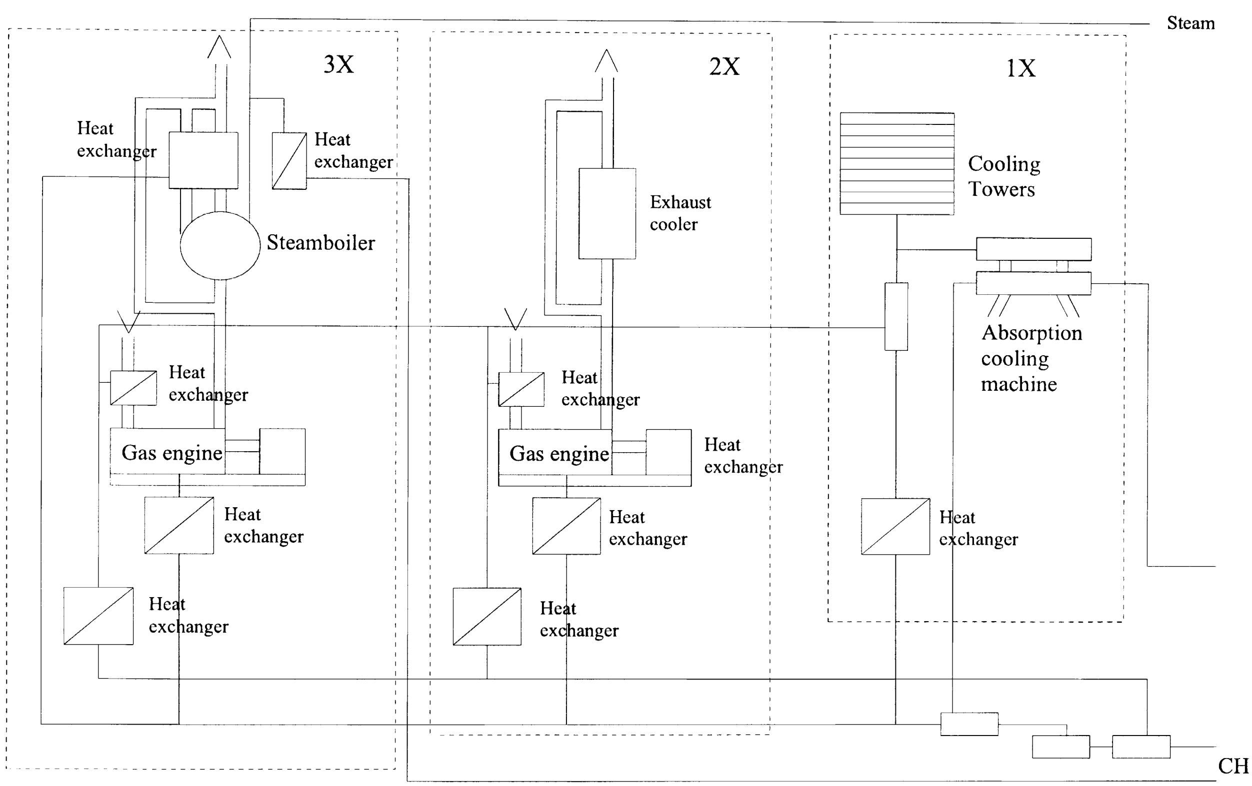

Fig. 2. The power plant (the seven cooling units, connected with the absorption chiller are not shown in this figure).

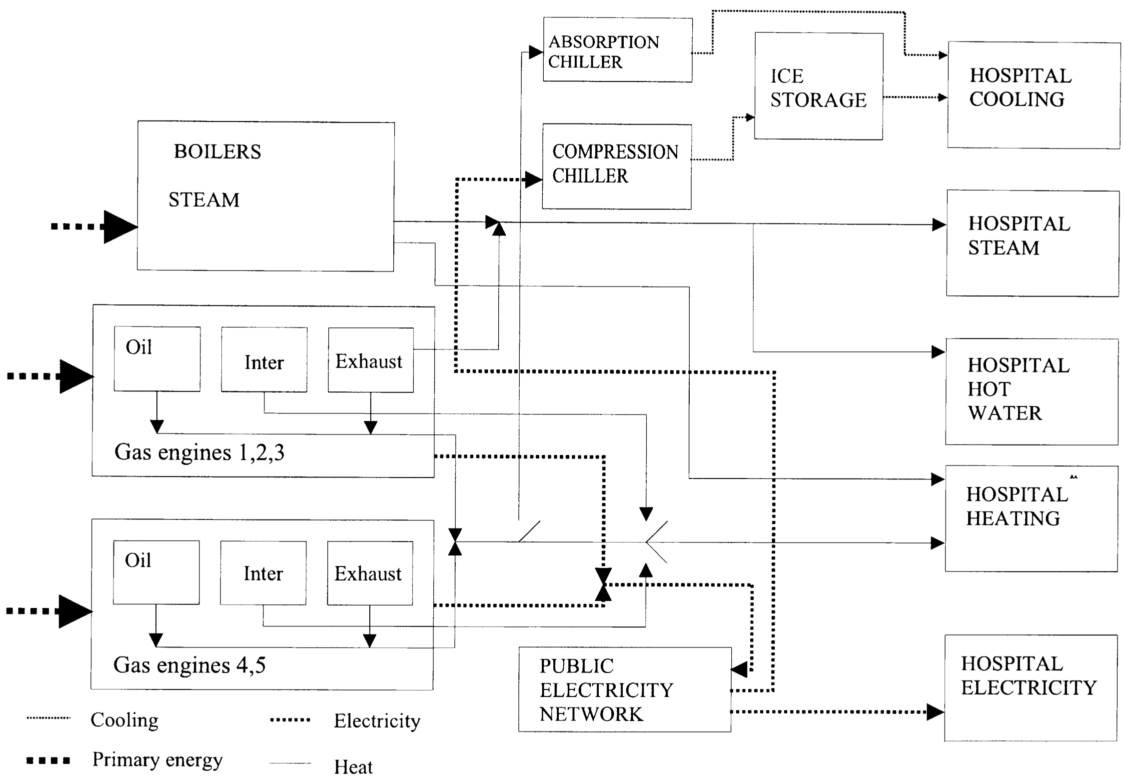

Fig. 3. The energy flows of the power plant and cooling installations.

numerical program, it is very time efficient on vector operations and optimization problems. (2) Model validation, by putting the model equations, exactly as they are presented in this paper in a symbolic computation software program like Maple (see Appendix A), the model equations can be theoretically validated. In the project, this benefit has successfully been used to correct preliminary errors in the model equations. The presented model syntax has also a drawback, it is perhaps more difficult to follow than a common model syntax.

3.1. Design a model

The model is based on energy flows. In Fig. 3 the energy flows (heat, cooling, electricity and primary energy) are shown.

3.2. Define non-controllable and controllable inputs and the output

The non-controllable input consists of: the demand for cooling (**QcA**), heating (**QhA**), electricity (**ElA**), steam (**msA**), hot water (**mlA**), and the energy price for gas (gpB (boilers), gpG (gas engines)) and electricity (**Epb**, **Eps**). The values of these variables are based on measurements and available utility rates. The controllable input consists of: the set points of the gas engine group 1 (**G13**) and group 2 (**G45**), and the set points of the mechanical chiller (**CCD**) and the absorption chiller (**ACD**). The output consists of: total profit (**Totp**), the primary energy (**Qprim**), the wasted useful energy (**Ekill**), and the cooling energy of the ice storage tanks (**QcB**).

3.3. Define constraints

The controllable inputs (setpoints of: **G13**, **G45**, **CCD**, **ACD**) are constrained by a minimum of 0 (represents switching off) and a maximum of 1 (represents maximum capacity). The state-of-charge of the ice storage tanks (**QcBsum**) is constrained with 0 (represents empty tanks) and QcBmax (full loaded tanks). Furthermore, the Academic hospital is connected to the public electricity grid. The supply of electricity is therefore guaranteed. The capacity of the boilers is much higher than the maximum heat demand, the supply of heat is therefore guaranteed. So no extra constraints are needed for electricity and heating. Fig. 4 shows the principle of modeling and optimization together with the non-controllable and controllable inputs and the output and constraints.

3.4. Define optimization criteria

The goal is to optimize the operation of the controllable input variables (set points) of: gas engine group 1 (**G13**), group 2 (**G45**), the compressor (**CCD**) and absorption chillers (**ACD**), using an optimization strategy to minimize

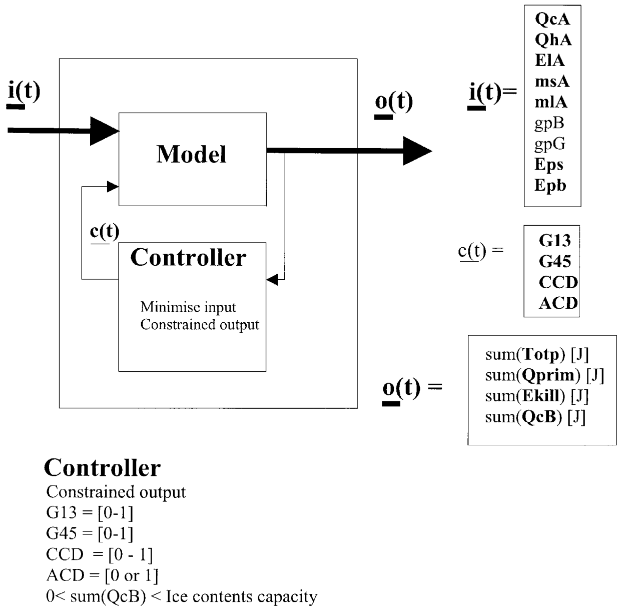

Fig. 4. The principle of modeling and optimization.

the chosen cost function. The next three optimization strategies are considered:

- *Strategy 1:* maximize the profit;
- *Strategy 2:* minimization of the primary energy use with the constraint that the profit is greater than zero;
- *Strategy 3:* minimize the primary energy use.

3.5. Build a numerical model

In Table 1 the input and output of the present components of the installation is summarized. The five gas engines are divided into two groups. First, G13 are the gas engines 1–3 with sub components: (1) electricity, (2) exhaust-heat exchanger to steam, and (3) exhaust-, inter- and oil-heat exchanger to heating of Academic Hospital. Second, G45 are the gas engines 4 and 5 with sub components: (1) electricity, and (2) exhaust-, inter- and oil-heat exchanger to heating of Academic Hospital. The efficiencies of the gas engine components depend on the operation of the gas engines. For example, when the intercoolers are disconnected, the electricity production efficiency increases and the heat production efficiency decreases. The three boilers, the seven mechanical chillers (CCD) and the ice storage tanks are each considered as one system. When more heat is produced than demanded by the hospital, the absorption chiller (ACD) can be switched on. Excessive amount of heat is then used for cooling. The ice storage has only a small heat gain from the surroundings. The efficiencies of the CHP units and chillers depend on their setpoints, according to the manufacture specifications. All other efficiencies are modeled as constants.

Table 1
Input and output descriptions of the components

Description of component	Input	Output
Hospital cooling	Cooling needs	–
Hospital steam	Steam needs	–
Hospital hot water	Hot water needs	–
Hospital heat	Heating needs	–
Hospital electricity	Electricity needs	–
Gas engines 1–3	Primary energy (gas)	Electricity, heat
Gas engines 4, 5	Primary energy (gas)	Electricity, heat
Boilers	Primary energy (gas)	Heat
Absorption chiller (ACD)	Heat	Cooling
Compression chiller (CCD)	Electricity	Cooling
Ice storage	Cooling	Cooling
Public electricity network	Electricity	Electricity
Switch ACD	Switching of the ACD when heat is available	
Switch intercoolers	Switching of intercoolers for extra heating needs	

The presented model is vector oriented. Furthermore, the next functions are used in the model representation ($\boldsymbol{x}$ is a vector variable):

$$\mathrm{posvec}(\boldsymbol{x}) = \tfrac{1}{2}\mathrm{abs}(\boldsymbol{x}) + \tfrac{1}{2}\boldsymbol{x} \tag{1}$$

$$\mathrm{negvec}(\boldsymbol{x}) = -\tfrac{1}{2}\mathrm{abs}(\boldsymbol{x}) + \tfrac{1}{2}\boldsymbol{x} \tag{2}$$

The next simple property can be derived from Eqs. (1) and (2):

$$\boldsymbol{x} = \mathrm{posvec}(\boldsymbol{x}) + \mathrm{negvec}(\boldsymbol{x}) \tag{3}$$

These functions are used to cope with different parameters for positive and negative elements of $\boldsymbol{x}$. For example to calculate the electricity profit, positive elements of the electricity balance vector have to be multiplied by the sale price of electricity and negative elements have to be multiplied by the purchase price of electricity (see Eq. (20)). Another function used in the model is:

$$\mathrm{sign}(\boldsymbol{x}) : \begin{cases} 1, & \text{if } \boldsymbol{x} > 0 \\ 0, & \text{if } \boldsymbol{x} = 0 \\ -1, & \text{if } \boldsymbol{x} < 0 \end{cases} \tag{4}$$

Since $\boldsymbol{x}$ is a vector, the result of sign($\boldsymbol{x}$) is also a vector with positive values of $\boldsymbol{x}$ replaced by 1, negative values of $\boldsymbol{x}$ replaced by -1, and zero values of $\boldsymbol{x}$ are unchanged. This function is used for switching the supply heat to the absorption chiller (see Eq. (10)).

3.5.1. Model equations

Fig. 3 is used as a guideline for the model equations. The primary energy power equations for the gas engines are:

$$\mathbf{P13} = \mathbf{G13}\, g_{\max 13} H \tag{5}$$

$$\mathbf{P45} = \mathbf{G45}\, g_{\max 45} H \tag{6}$$

The electrical power of the compressor chillers:

$$\mathbf{ElC} = \mathbf{CCD}\, \mathrm{CCD}_{\max} \tag{7}$$

The electricity balance (negative values mean a shortage of electricity):

$$\mathbf{Elbal} = \mathbf{P13}\,\eta_{\mathrm{E13}} + \mathbf{P45}\,\eta_{\mathrm{E45}} - \mathbf{ElC} - \mathbf{ElA} \tag{8}$$

The heat balance:

$$\mathbf{QCHbal} = \mathbf{P13}(\eta_{h13A} + \eta_{\mathrm{h13I}}) + \mathbf{P45}(\eta_{\mathrm{h45A}} + \eta_{\mathrm{h45}I}) - \mathbf{QhA} \tag{9}$$

The electrical and thermal efficiencies of the CHP units depend on their setpoints, according to the manufacture specifications. The switching of the absorption chiller (positive elements of **QCHbal** mean that the absorption chiller is allowed to switch on and is represented by ones in the variable **QhSW**, negative elements of **QCHbal** mean that the absorption chiller is not allowed to switch on and is represented by zeros):

$$\mathbf{QhSW} = \mathrm{posvec}(\mathrm{sign}(\mathbf{QCHbal})) \tag{10}$$

The unused heat due to the heat supply to the absorption chiller exceeding the maximum design heat supply:

$$\mathbf{QACDback} = \mathrm{posvec}(\mathbf{QCHbal} - \mathrm{QcSmax}) \tag{11}$$

The used heat from the gas engines to the absorption chiller and heat supply for the central heating of the building:

$$\mathbf{QhACD} = \mathbf{QhSW}\,\mathbf{ACD}(\mathrm{posvec}(\mathbf{QCHbal}) - \mathbf{QACDback}) \tag{12}$$

$$\mathbf{QhCH} = \mathbf{P13}(\eta_{\mathrm{h13A}} + \eta_{\mathrm{h13I}}) + \mathbf{P45}(\eta_{\mathrm{h45A}} + \eta_{\mathrm{h45I}}) - \mathbf{QhACD} \tag{13}$$

The heat balance of the boilers (positive values mean a heat demand for the boilers), the heat demand of the boilers and the gas supply to the boilers:

$$\mathbf{QBbal} = -\mathrm{negvec}(\mathbf{QhCH} - \mathbf{QhA}) - \mathbf{P13}\,\eta_{\mathrm{h13S}} + \mathbf{msA}(h_{\mathrm{st}} - h_{\mathrm{cwa}}) + \mathbf{mlA}(h_{\mathrm{hwa}} - h_{\mathrm{cwa}}) \tag{14}$$

$$\mathbf{QB} = \mathrm{posvec}(\mathbf{QBbal}) \tag{15}$$

$$\mathbf{mgB} = \frac{\mathbf{QB}}{H\eta_{\mathrm{hK}}} \tag{16}$$

The cooling power supply for the ice storage tanks:

$$\mathbf{QcB} = \mathbf{ElC}\,\eta_{\mathrm{cC}} + \mathrm{negvec}(\mathbf{QhACD}\,\eta_{\mathrm{cS}} - \mathbf{QcA}) \tag{17}$$

The thermal efficiencies of the chillers depend on their setpoints according to the manufacture specifications. If the cooling supply of the absorption chiller exceeds the cooling demand, the negvec function replaces the positive elements by zeros, representing that the absorption chiller cannot charge the ice storage system. The wasted useful heat supplied directly or indirectly by the gas engines:

$$\mathbf{Ekill} = -\,\mathrm{negvec}(\mathbf{QBbal}) + \mathrm{posvec}(\mathbf{QhCH} - \mathbf{QhA}) + \mathrm{posvec}(\mathbf{QhACD}\,\eta_{\mathrm{cS}} - \mathbf{QcA}) \tag{18}$$

The three terms on the right hand side of Eq. (18) represent the wasted useful energy for, respectively, the steam production, the heating of the hospital, and cooling produced by the absorption chiller. The total primary energy equivalent of the gas flow and electricity supply:

$$\mathbf{Qprim} = H\,\mathbf{mgB} + \mathbf{P13} + \mathbf{P45} - \mathrm{negvec}\,\frac{\mathbf{Elbal}}{\eta_{\mathrm{Epub}}} \tag{19}$$

The electricity profit (positive values mean profits), the gas cost (positive values mean costs), and the total profit (positive values mean profits) is given by:

$$\mathbf{EP} = \mathbf{Eps}\,\mathrm{posvec}(\mathbf{Elbal}) + \mathbf{Epb}\,\mathrm{negvec}(\mathbf{Elbal}) \tag{20}$$

$$\mathbf{gP} = \mathrm{gpB}\,\mathbf{mgB} + \mathrm{gpG}\,(g_{\mathrm{max13}}\,\mathbf{G13} + g_{\mathrm{max45}}\,\mathbf{G45}) \tag{21}$$

$$\mathbf{Totp} = \mathbf{EP} - \mathbf{gP} \tag{22}$$

Note that the electricity prices for purchase and sale are vectors because they depend on the time (day and night values). The gas prices for the gas engines and boilers are different fixed prices.

3.6. Select an appropriate time scale

The time scale is a very important factor when using the quasi-steady approach. The switching of gas engines is limited to once during the day (16 h) and once during the night (8 h). The ice storage can be loaded from empty to full capacity within 8 h. The electricity prices are different during the day and night. When selecting a time-step of 16 h (day) and 8 h (night), the optimization horizon can be limited to 24 h. In this situation, it is possible to generate cooling from the compressor chiller to the ice storage during the night when the electricity is cheaper and is used during the day. Using a total simulation period of 1 year and a resolution of two steps a day, each variable contains 730 states.

3.7. Build a numerical optimization routine and calculate the optima

The goal is to optimize the controllable inputs in such a way that the output satisfies the given criteria and the constraints. A well-known problem with non-linear optimization is that the calculated solution is not the global optimum but a local optimum. In order to prevent this and also to get a fast convergence, a good starting point is necessary. A back-tracking method [1] is used for this problem and it consists of the following steps:

- divide all controllable inputs into discrete steps;
- calculate all possible combinations of the controllable inputs;
- simulate all combinations;
- select the best solution (back-tracking) from all possible solutions given the optimization criteria.

Using the back-tracking method, it is necessary to compute all combinations from the next values for the controllable inputs: **G13** and **G45** (0, 0.25, 0.5, 0.75, 1), **CCD**

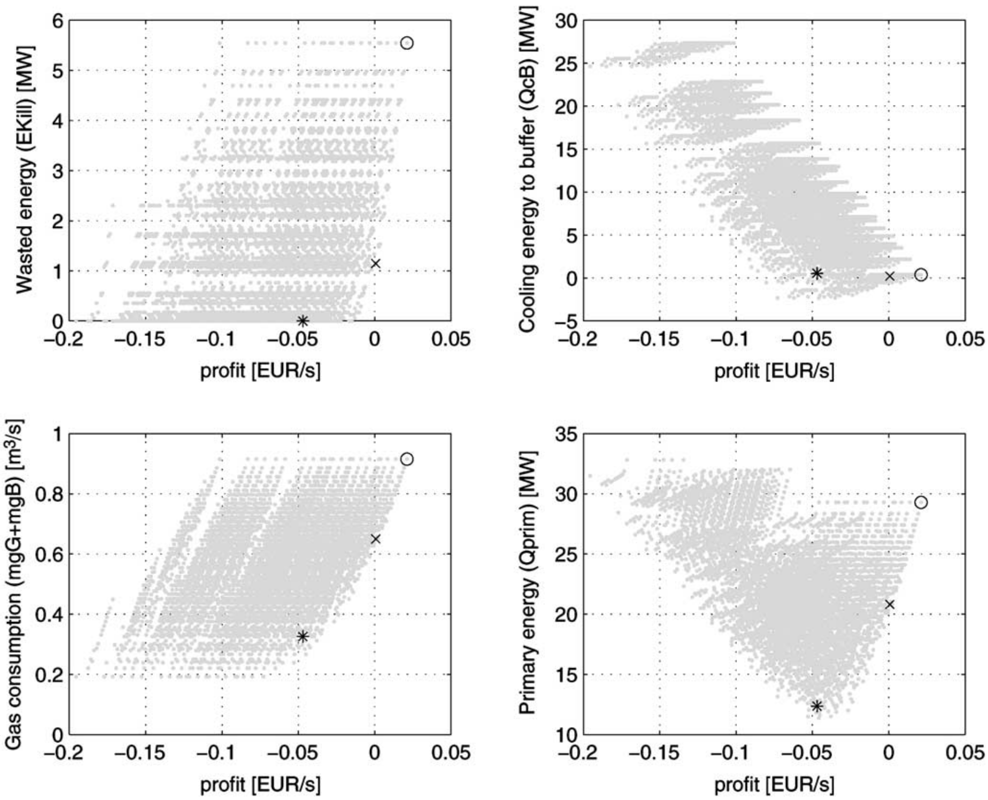

Fig. 5. The results of the back-tracking method. The wasted energy, cooling energy to the buffer, gas consumption and used primary energy against the profit.

(0, 0.20, 0.35, 0.50, 1) and **ACD** (0 or 1). There are 250 possibilities per period. A time frame of two periods must be evaluated. Given a day and night period then 62,500 possibilities are present. Fig. 5 shows the results of the back-tracking method. The wasted energy, cooling energy to the buffer, gas consumption and used primary energy are plotted against the profit. Considering the constraint for the ice buffer, the next optima are selected: The maximum profit (○), the absolute minimum used primary energy (∗) and the minimum used primary energy with a constraint that the profit is positive (×). This method gives a rough estimation of the optima. Since the optimization problem is non-linear and discontinues (see also [7]), a Sequential Quadratic Programming (SQP) routine of the MatLab Optimization Toolbox [5] is used to refine the optimization.

4. Results

4.1. The non-controllable input signals of the model i(t)

Fig. 6 shows some of the non-controllable inputs of the model: cooling, heating, electricity and steam needed for the Academic Hospital against time. The time series are simulated time series based on global values. The time period is 1 year and is shown in hours after 1 October. Other non-controllable inputs are the prices for purchasing and selling electricity and the price of gas.

4.2. The optimization results

In Fig. 7 the output signals: profit, primary energy used, wasted energy and optimal operation of gas engines 1–3, are shown, when using optimization strategy 2, for a period of 1 year. Also, the details on the optimal operation of gas engines 4 and 5, the mechanical chillers and the absorption chiller are calculated. The yearly characteristics of the three strategies are listed in Table 2.

4.3. Comparing the different strategies

When comparing the different strategies, the primary energy versus the profit and the wasted useful heat versus

Table 2
The year characteristics of the optimization results of the strategies

Year characteristic	Strategy 1	Strategy 2	Strategy 3
Total profit (€)	700000	0	−1500000
Gas usage boilers (m^3)	1290000	1860000	4300000
Gas usage gas motors (m^3)	27900000	20150000	8200000
Total heat demand (MWh)	69000	69000	69000
Total cool demand (MWh)	17000	17000	17000
Electricity for hospital (MWh)	24000	24000	24000
Electricity for cooling (MWh)	800	1100	4800
Total electricity produced (MWh)	87800	62700	25500
Total primary energy (MWh)	259700	195700	120000
Wasted useful heat (MWh)	33700	12500	0

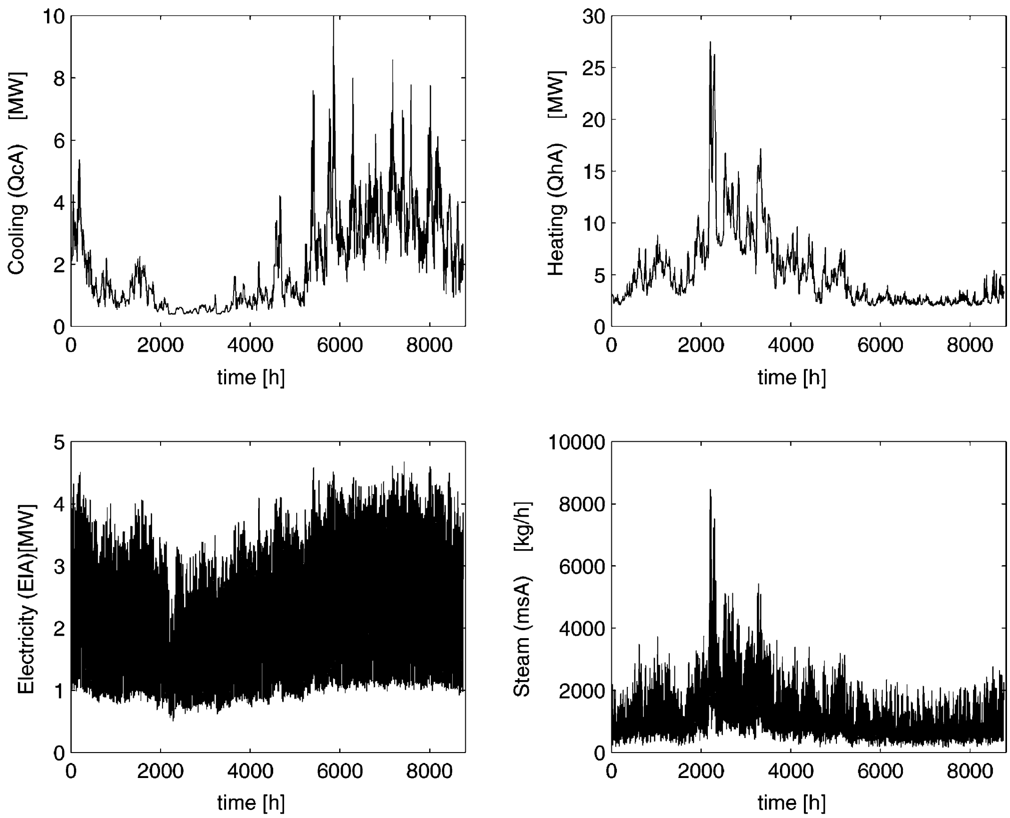

Fig. 6. The non-controllable inputs of the model: cooling, heating, electricity and steam needed for the Academic Hospital against time.

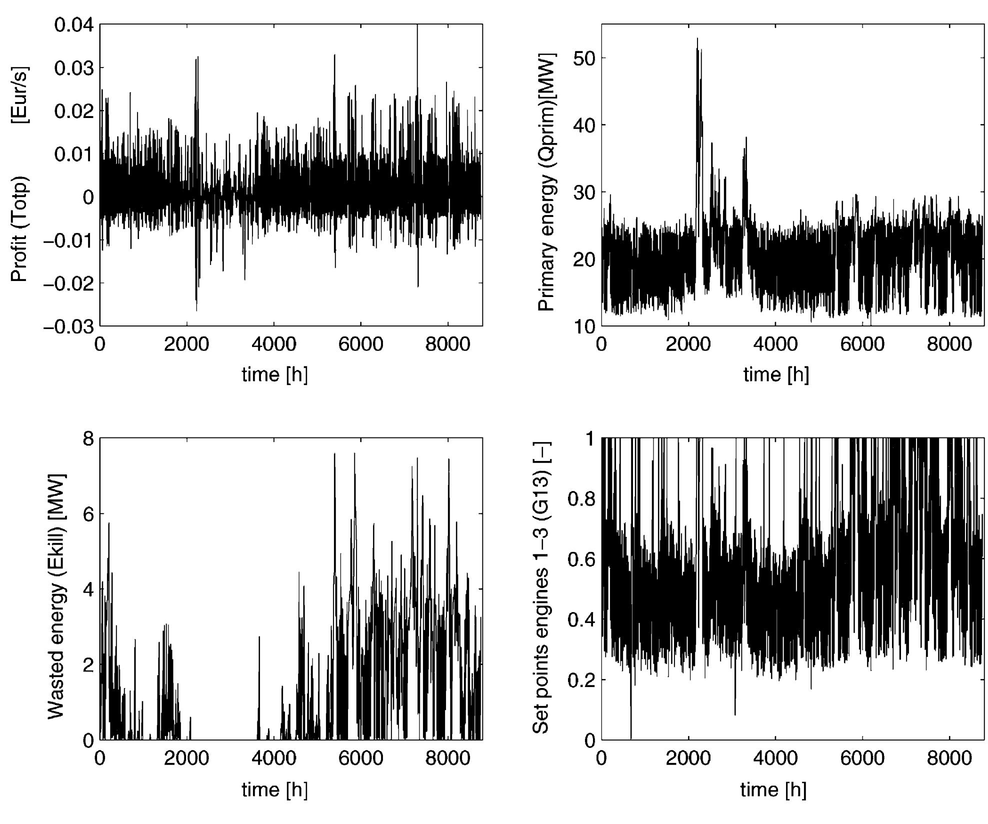

Fig. 7. The output signals: profit, used primary energy, wasted energy and set point of gas motors 1–3 against time.

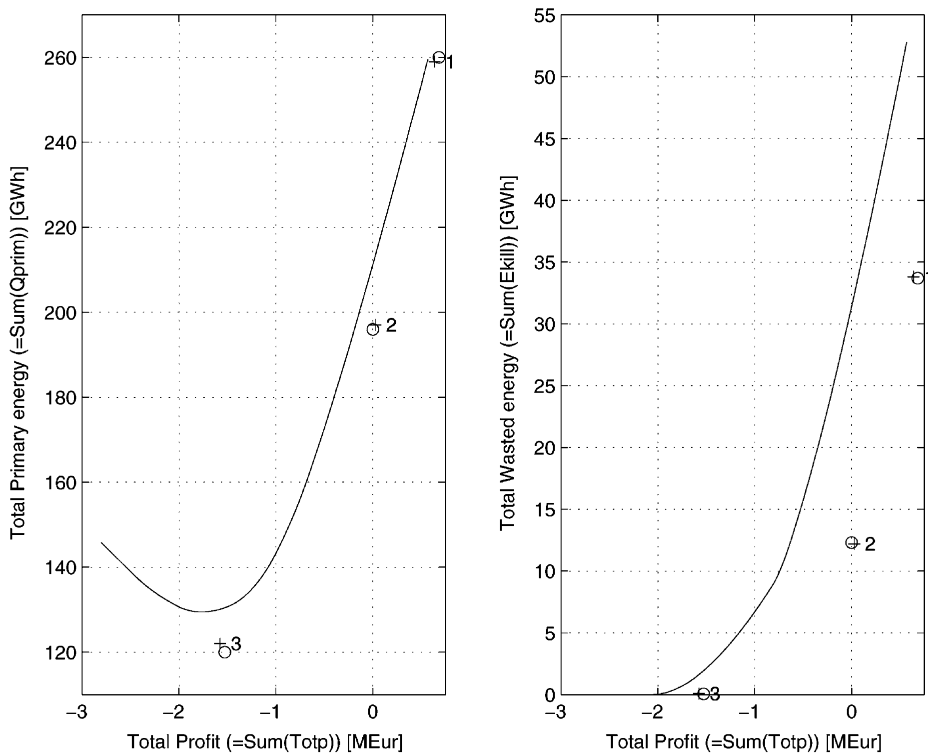

Fig. 8. The yearly primary energy and the yearly wasted energy versus the yearly profit. (○) Result of SQP optimization method; (+) result of the back-tracking method; (1, 2, 3) label for strategy 1–3. The line (–) is calculated from varying the set points of all gas engines from 0 to 100% with the assumption that no energy can flow to or from the ice buffer (i.e. assuming no storage capacity of the ice buffer).

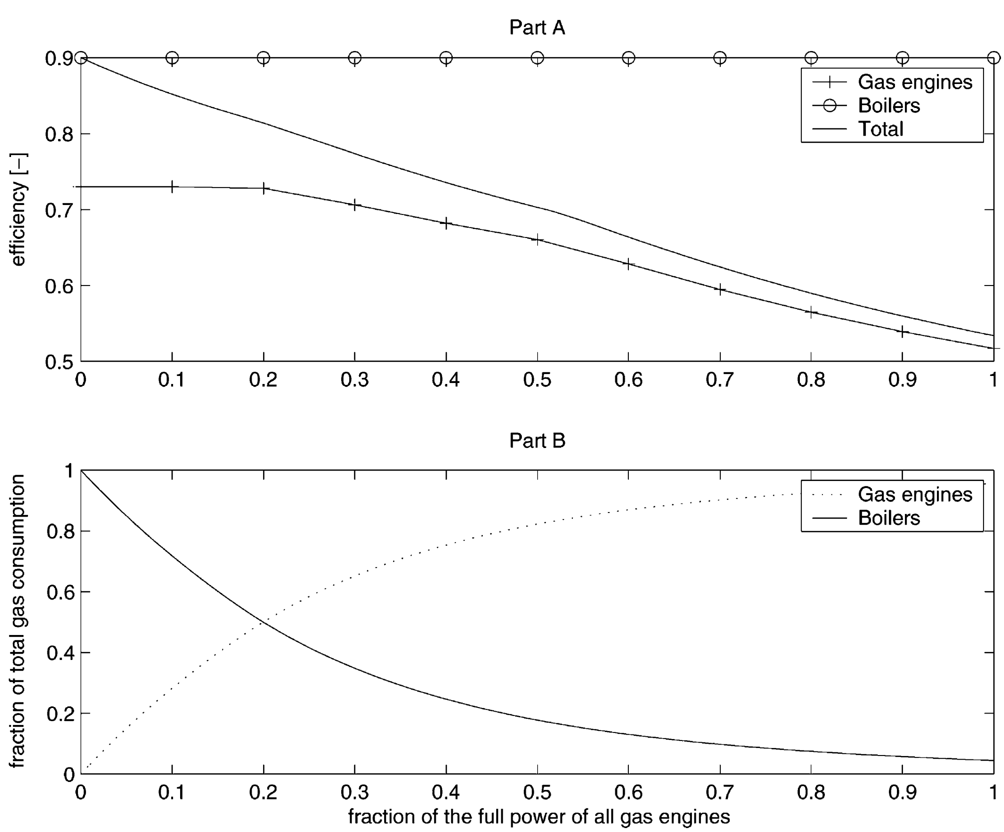

Fig. 9. (A) The efficiency of the boilers and gas motors; (B) the fraction of gas consumption of the boilers and gas motors.

the profit are shown in Fig. 8. The differences between the back-tracking method and the SQP method seems to be small on the total scale of possible set points. Still the SQP method gives always a higher profit (at least 0.05 million €) than the back-tracking method. When the set points of all the gas engines are held at 1 all year, the presence of the ice buffer can give an extra profit of 0.1 million € and a reduction of 20 GWh (equal to the amount of heating 1000 average Dutch housess) of the wasted useful heat, each year.

4.4. The total efficiency of the power plant

From the simulation results it is possible to look at the overall efficiency of the power plant. In Fig. 9(A), the efficiencies of the boilers and gas engines are shown and in Fig. 9(B) the fraction of gas consumption of the boilers and gas engines is shown. The total efficiency of the power plant is calculated from the efficiencies of the gas engines and boilers and weighted with the fraction of the total gas consumption of the gas engines and boilers. The gas engines are designed for an overall efficiency of 0.73 and the boilers 0.9. When the gas engines are off all year, the total efficiency equals the efficiency of the boilers. When the mean fraction of full power of the gas engines is 0.20, then both boilers and gas engines have equal gas consumption. The total efficiency is 0.82. When the mean fraction of full power of the gas engines exceeds 20% the efficiency of the gas engines decreases because the gas engines produce more heat than needed for the hospital. The total efficiency drops to 0.53 when the gas engines are set to 1 all of the year.

5. Conclusions

A model for a complex hospital combined heating, power and cooling plant is presented. The model is based on vector equations. The main advantages of this type modeling are a time efficient computation and the model can be checked analytically. The simulations facilitate an environment for testing different strategies for an optimal operation on a yearly base. Three strategies are used for the optimization of the operation of the power plant, the first optimization strategy is a pure economic optimization. This strategy gives a profit of 0.7 million € with 260 GWh of used primary energy. The operation for this situation can be summarized as: (a) all gas engines are at the maximum level during the day and the night; (b) the ice storage tanks are filled at night. The second optimization is a pure energy optimization. This strategy gives a loss of 1.5 million € with 120 GWh of used primary energy. The third optimization is an energy optimization with the constraint that the profit is greater than zero. This strategy gives a profit of 0.0 million € with 196 GWh of used primary energy. For the last two optimizations, the operation is calculated in detail. It is not possible to summarize these results in a simple way just like the first optimization. The described method is also applicable for other similar optimization problems. The thermal and electric efficiencies presented in this paper are modeled at a much lower level and are dependent on engine percentage loads. Implementation of more complex models is left over for future research.

Appendix A.

Validation of the model equations in Maple.

```
Model

> posvec:=(x)->(abs(x)+x)/2;
> negvec:=(x)->(-abs(x)+x)/2;
> siggn:=(x)->signum(x);
> P13:=gmax13*H*G13;
> P45:=gmax45*H*G45;
> ElC:=CCD*CCDmax;
> Elbal:=P13*rE13+P45*rE45-ElC-ElA;
> QCHbal:=P13*(rh13A+rh13I)+P45*(rh45A+rh45I)-QhA;
> QhSW:=posvec(siggn(QCHbal));
> QACDback=posvec(QCHbal-QcSmax);
> QhACD:=QhSW*(posvec(QCHbal)-QACDback)*ACD;
> QhCH:=P13*(rh13A+rh13I)+P45*(rh45A+rh45I)-QhACD;
> QKst:=(hst-hcwa)*msA + (hhwa-hcwa)*mlA;
> QBbal:=-negvec(QhCH-QhA)+QKst - P13*rh13s;
> QB:=posvec(QBbal);
> mgB:=QB/(rhK*H);
> QcB:=ElC*rcC+negvec(QhACD*rcS-QcA);
> Ekill:=-negvec(QBbal)+posvec(QhCH-QhA)+posvec(QhACD*rcS-QcA);
> Qprim:=H*mgB+P13+P45 -negvec(Elbal)/rEpub;
> EP:=Eps*posvec(Elbal) + Epb*negvec(Elbal);
> gP:=gpB*mgB+gpG*(gmax13*G13+gmax45*G45);
> Totp:=EP-gP;
> Sloss:=(1-rcS)*QhACD;
> Closs:=(1-rcC)*ElC;
> Kloss:=(1-rhK)*H*mgB;
> Gloss:=P13*(1-rE13-rh13s-rh13A-rh13I) +
  P45*(1-rE45-rh45A-rh45I) ;
> Euit:=QcA+QKst+QhA+ElA+QcB+Elbal+Kloss+Gloss+Sloss+Closs+Ekill
  ;
> Ein:=H*mgB + P13 + P45;
> Etot:=Ein-Euit;
> eq1:=simplify(Etot);
>
                                   eq1 := 0
```

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