

# Design parameters influencing the operation of a CHP plant within a micro-grid: application of the ANOVA test

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**Abstract.** Combined heat and power systems are widely recognized as a cost-effective solution for the achievement of sustainable and energy efficiency goals. During the last decade, cogeneration systems have been extensively studied from both the technological and operational viewpoints. However, the operation of a cogeneration system is a topic still worth of investigation. In fact, along with the determination of the optimal configurations of the combined heat and power systems, it is likewise fundamental to increase the awareness on the design and cost parameters affecting the operation of cogeneration systems, especially if considering the micro-grid in which they are inserted. In this direction, this paper proposed a mixed integer linear programming model with the objective of minimizing the total operational costs of the micro-grid. Different scenarios include the satisfaction of the cooling demands of the micro-grid as well as the opportuneness to include a heat storage. The influence of the main design and cost parameters on the operation of the micro-grid has been assessed by adopting the statistical tool ANOVA (Analysis Of Variance). The model and the experimental application of the ANOVA have been applied to a micro-grid serving a hospital located in the South of Italy.

## 1 Introduction

Combined heat and power (CHP) systems have been widely recognized as a promising solution to achieve energy sustainability targets [1]. The main advantage of CHP systems relies in the simultaneous production of heat and power [2], which allows CHP playing an important role in reducing the environmental impact of the traditional power generation [3]. Additionally, CHP systems permit a large amount of energy savings, estimated around the 30%, if compared with the separate production of electricity and heat [1, 4]. With respect to the normative aspect, the European Directive 2004/8/EC supports the diffusion of CHP systems by providing financial contributions and subsidies, making this technology economically more attractive [5].

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However, the determination of the actual convenience of CHP systems is a multi-faceted problem, strongly depending on technological, operational and energy management aspects. With reference to the mere technological issues, relevant scientific contributions address the optimal sizing of the CHP system. In this regard, Bianchi et al. [6] performed a thermo-economic analysis to define the optimum sizing of the components of micro-CHP for residential applications. Ren et al. [2] developed a mixed integer non-linear programming (MINLP) model minimizing the annual cost of a residential CHP plant combined with a storage tank and a back-up boiler. Other authors implemented optimization models focussing on the effectiveness of thermal storages [7, 8], compared different prime mover technologies [9] or, jointly, evaluated the performances of different prime movers with respect to various thermal storage units [10].

Other literature includes operational and management strategies in their models [11 – 16]. Among these, Manservigi et al. [11] developed a dynamic programming algorithm for the optimal operation strategy of micro-CHP equipped with thermal and electrical storages for residential applications. Diaz et al. [13] proposed an optimization-based controller to target the maximization of the profit of a CHP plant. Costa and Fichera [14] presented an optimization model for sizing a CHP plant equipped with a thermal storage and operating within a micro-grid. Similarly, Gonzalez-Pino et al. [15] investigated sizing and design purposes of a residential micro-CHP with a thermal storage.

The aforementioned contributions are mainly focussed on the formulation of optimization models or deepened particular technological issues related to the main components of CHP within a micro-grid. In addition to these works, a substantial part of literature agrees on the need to determine the influence that a particular design parameter have on the CHP considered as a whole. To target this goal, some authors conducted sensitivity analyses to determine the key parameters affecting the decision to install a CHP system [2, 17]. The sensitivity analysis evaluates changes in the model outputs with respect to different inputs. Even if widely diffused, a sensitivity analysis does not permit to draw inference about the influence of different independent design parameters on the system. Moreover, it does not add further knowledge on the reciprocal influence between two parameters with reference to the whole system. To solve these aspects, other authors implemented the statistical tool called ANalysis Of VAriance (ANOVA) able to determine the effects of different parameters on the result [18, 19]. To our knowledge, there is a limited application of the ANOVA test in the field of CHP technologies. Examples in this sense have been found in the works of [20, 21]. Specifically, Torchio et al. [20] applied the ANOVA for the experimental analysis of the single and combined effects of the main variables on the cogenerative performance of a PEMFC (proton exchange membrane fuel cell) stack, whilst Cali et al. [21] analysed the significance of the variables on the operation of a SOFC (solid oxide fuel cell) CHP.

Despite the efforts of the previous cited papers and except for the works [20] and [21], the current literature lacks the application of the ANOVA approach in the context of CHP operational planning, especially if considering a cogeneration plant operating in the context of a micro-grid and combined with an auxiliary boiler and a heat storage. Therefore, the aim of this paper is to enlarge the comprehension of the design parameters that effect the operation of a CHP plant through the application of the ANOVA test. Firstly, a mixed-integer linear programming model is formulated to assess the optimal operational strategy of a CHP inserted within a micro-grid and combined with an auxiliary boiler and a heat storage. Subsequently, the ANOVA test is applied in order to evaluate the effect of each design parameters on the results.

The paper is structured as follows. Section 2 presents the model and the ANOVA test. Section 3 introduces the case study. Results are discussed in Section 4 and, finally, Section 5 provides the conclusions.

## 2 The mathematical model

The optimal operational strategy of a CHP plant is formulated as a mixed integer linear programming model previously developed by the authors [14].

The goal of the model is to minimize the overall costs that contribute to the operation of the cogeneration plant, i.e. annual costs for natural gas  $C_G$ , for electrical energy  $C_E$  and for maintenance  $C_{MAN}$ , whilst taking into account annual revenue  $R_E$  from the CHP system. The objective function to be minimized can be, therefore, expressed as:

$$Z = C_G + C_E + C_{MAN} - R_E \quad (1)$$

Each term of Eq.(1) can be further characterized for each month  $m$  and hour  $h$  as:

$$C_G = \sum_{m=1}^{12} \sum_{h=1}^{24} G_{mh} \cdot C_{u,g} \cdot d_m \quad (2)$$

$$C_E = \sum_{m=1}^{12} \sum_{h=1}^{24} E_{s,mh} \cdot C_{u,e} \cdot d_m \quad (3)$$

$$C_{MAN} = \sum_{m=1}^{12} \sum_{h=1}^{24} E_{mh}^{CHP} \cdot C_{u,man} \cdot d_m \quad (4)$$

$$R_E = \sum_{m=1}^{12} \sum_{h=1}^{24} E_{out,mh}^{CHP} \cdot P_{u,e} \cdot d_m \quad (5)$$

The annual cost for natural gas  $C_G$  is calculated as in Eq.(2), where  $G_{mh}$  is the imported natural gas at hour  $h$  for month  $m$  [ $\text{Nm}^3$ ],  $C_{u,g}$  the unit of natural gas [ $\text{€}/\text{Nm}^3$ ] and  $d_m$  the number of days for each month  $m$ . The annual cost for electrical energy  $C_E$  in Eq.(3) is calculated considering the electrical energy imported from the grid  $E_{s,mh}$  at hour  $h$  for month  $m$  [kWh], the unit cost of electrical energy  $C_{u,e}$  [ $\text{€}/\text{kWh}$ ] and the number of days for each month  $m$ ,  $d_m$ . The annual cost for maintenance  $C_{MAN}$  is calculated as in Eq.(4), where  $E_{mh}^{CHP}$  is the electrical energy from the CHP at hour  $h$  for month  $m$ ,  $C_{u,man}$  the unit of maintenance [ $\text{€}/\text{kWh}$ ] and  $d_m$  the number of days for each month  $m$ . The annual revenue for the CHP system  $R_E$  is calculated as in Eq.(5), where  $E_{out,mh}^{CHP}$  is the electrical energy produced by CHP [kWh] and exported to the grid at hour  $h$  of month  $m$ ,  $P_{u,e}$  the unit price of electricity [ $\text{€}/\text{kWh}$ ] and  $d_m$  the number of days for each month  $m$ . The constraints of the model are:

$$E_{tot,mh} = E_{c,mh} + E_{cool,mh}, \forall m, h \quad (6)$$

$$G_{mh} = G_{mh}^{BO} + G_{mh}^{CHP}, \forall m, h \quad (7)$$

$$E_{mh}^{CHP} = E_{in,mh}^{CHP} + E_{out,mh}^{CHP}, \forall m, h \quad (8)$$

$$E_{in,mh}^{CHP} + E_{s,mh} \geq E_{tot,mh}, \forall m, h \quad (9)$$

$$E_{in,mh}^{CHP} \leq x_{mh}^{CHP} \cdot P_{CHP} \cdot t, \forall m, h \quad (10)$$

$$H_{mh}^{CHP} + H_{mh}^{BO} \geq H_{c,mh}, \forall m, h \quad (11)$$

$$G_{mh}^{BO} \geq \frac{H_{mh}^{BO}}{\eta_{BO} \cdot LHV}, \forall m, h \quad (12)$$

$$H_{mh}^{BO} \leq x_{mh}^{BO} \cdot P_{BO} \cdot t, \forall m, h \quad (13)$$

$$G_{mh}^{CHP} \geq \frac{1}{LHV} \left( \frac{H_{mh}^{CHP}}{\eta_{th}^{CHP}} + \frac{E_{mh}^{CHP}}{\eta_e^{CHP}} \right), \forall m, h \quad (14)$$

The total electrical energy consumption  $E_{tot,mh}$  in Eq.(6) is evaluated distinguishing between the electrical energy demand for cooling  $E_{cool,mh}$  [kWh] and electrical energy consumption  $E_{c,mh}$  [kWh]. The imported natural gas  $G_{mh}$  [Nm<sup>3</sup>] in Eq.(7) is due to both the boiler  $G_{mh}^{BO}$  [Nm<sup>3</sup>] and the CHP system  $G_{mh}^{CHP}$  [Nm<sup>3</sup>]. As can be inferred from Eq.(8), the total electrical energy produced by the CHP  $E_{mh}^{CHP}$  [kWh] is intended to satisfy the energy demand of end-users  $E_{in,mh}^{CHP}$  [kWh] or to be sold to the grid  $E_{out,mh}^{CHP}$  [kWh]. Obviously, the total electrical consumption of users  $E_{tot,mh}$  [kWh] is satisfied by the electrical energy produced by the CHP  $E_{in,mh}^{CHP}$  [kWh] and/or from the electrical energy imported from the grid  $E_{s,mh}$  [kWh], as expressed in Eq.(9). The constraint formulated in Eq.(10) represents the total electrical energy produced by the CHP  $E_{mh}^{CHP}$  [kWh] and depends from the power size of the CHP,  $P_{CHP}$  [kW]. The binary variable  $x_{mh}^{CHP}$  is equal to 1 if the CHP operates at hour  $h$  of the month  $m$ , 0 otherwise;  $t$  is the time period. As regard to the thermal energy and similarly to the constraint developed for the electrical energy, Eq.(11) imposes that the sum of the thermal outputs of both the CHP system  $H_{mh}^{CHP}$  [kWh] and the boiler  $H_{mh}^{BO}$  [kWh] should satisfy the thermal demand of the users  $H_{c,mh}$  [kWh]. Eq.(12) balances the thermal energy at the boiler, being  $\eta_{BO}$  the efficiency of the boiler and LHV the lower heating value [kWh/Nm<sup>3</sup>], whilst Eq.(13) expresses the amount of thermal energy supplied by the boiler, having the power of the boiler  $P_{BO}$  [kW] and the binary variable  $x_{mh}^{BO}$  (equal to 1 if the boiler operates at hour  $h$  of the month  $m$ , 0 otherwise). The balance of the total energy at the CHP system is expressed as:

$$\begin{cases} E_{mh}^{CHP} = E_{in,mh}^{CHP} \cdot \frac{\eta_e^{CHP}}{\eta_e^{CHP} + \eta_{th}^{CHP}}, \forall m, h \\ H_{mh}^{CHP} = E_{in,mh}^{CHP} \cdot \frac{\eta_{th}^{CHP}}{\eta_e^{CHP} + \eta_{th}^{CHP}}, \forall m, h \end{cases} \quad (15)$$

Being  $\eta_e^{CHP}$  and  $\eta_{th}^{CHP}$  the electrical and thermal efficiencies of the CHP. Finally, the following constraints and balance equations refer to heat storage:

$$H_{acc,mh} = H_{acc,in,mh} + \Delta H_{acc,mh}, \forall m, h \quad (16)$$

$$\Delta H_{acc,mh} = H_{mh}^{BO} + H_{mh}^{CHP} - H_{c,mh}, \forall m, h \quad (17)$$

$$\sum_{h=1}^{24} \Delta H_{acc,mh} = 0, \forall m \quad (18)$$

$$H_{acc,min} \leq H_{acc,mh} \leq \Delta H_{acc,max}, \forall m, h \quad (19)$$

Eq.(16) is the balance equation for the thermal energy of the heat storage  $H_{acc,mh}$  [kWh] and takes into account the thermal energy stored at the beginning of each simulation period  $H_{acc,in,mh}$  [kWh] and the exchanged thermal energy  $\Delta H_{acc,mh}$  [kWh]. To evaluate the exchanged thermal energy  $\Delta H_{acc,mh}$ , the thermal energy from both the boiler and the CHP and the thermal energy consumption in the period should be considered, as expressed in Eq.(17). Obviously, Eq.(18) balancing the daily exchange of thermal energy from the heat storage. Finally, the lower and upper bounds for the thermal energy that can be stored are defined as in Eq.(19).

To conclude, the following equations ensure the non-negativity and existence of all introduced parameters and variables.

$$G_{mh}^{CHP}, G_{mh}^{BO}, E_{in,mh}^{CHP}, E_{out,mh}^{CHP}, E_{s,mh}^{CHP} \geq 0, \forall m, h \quad (20)$$

$$x_{mh}^{CHP}, x_{mh}^{BO} \in \{0, 1\} \tag{21}$$

$$\Delta H_{acc,mh} \in R, \forall m, h \tag{22}$$

### 2.1 The ANOVA test

Once the model has been defined, the further step consists of the analysis of the design parameters influencing the operation of the CHP system. To target this scope, the ANOVA test is conducted. The ANOVA is a statistical procedure here used to determine the “impact”, hereinafter defined *effect*, of one or more parameters on the objective function. The test examines two opposing hypothesis: the null hypothesis  $H_0$  is a statement of “little or no effect on the objective function”, whilst the alternate hypothesis  $H_1$  states the opposite [22]. In particular, the ANOVA distinguishes the total variation of the objective functions into two contributions; the first related to the variation between different optimized results and the second related to the variation within each group of optimized result. These two contributions are expressed by means of the sums of squares, as in Eq. (23) and Eq. (24):

$$SS(B) = \sum_{i=1}^m \sum_{j=1}^n (\bar{X}_i - \bar{X})^2 \tag{23}$$

$$SS(E) = \sum_{i=1}^m \sum_{j=1}^n (X_{ij} - \bar{X}_i)^2 \tag{24}$$

Where  $m$  denotes the number of groups of the optimized results and  $n$  the number of results of each group. The term  $SS(B)$  in Eq.(23) quantifies the variation between the different groups of optimized results and is calculated as the contributions from the squared distances of the mean of the group to the grand mean (related to all the data observed). The term  $SS(E)$  in Eq.(24) represents the variation within the groups and is calculated as the sum of the squared distances of the observation to the mean of the group.

The quantities  $SS(B)$  and  $SS(E)$  are then converted into “mean squares” representing an estimate of the variance and used in the ANOVA to determine whether parameters are significant:

$$MS(B) = \frac{SS(B)}{m-1} \tag{25}$$

$$MS(E) = \frac{SS(E)}{m-n} \tag{26}$$

The denominators of Eq.(25) and Eq.(26) represents the degree of freedom associated with  $SS(E)$  and  $SS(B)$ . Finally, in order to conduct the ANOVA, a test statistic following the  $F$ -distribution [23] is considered and is calculated as:

$$F - value = \frac{MS(B)}{MS(E)} \tag{27}$$

The  $F$ -value determines the  $p$ -value, i.e. the evidence against the null hypothesis  $H_0$ . In particular, the  $p$ -value is calculated comparing the  $F$ -statistic to the  $F$ -distribution expressed as  $(m-1)/(m-n)$ . The smaller the  $p$ -value, the stronger the evidence to reject  $H_0$ , i.e. the parameter has a significant effect on the objective function. For convention, it has been established that the effect of the parameter can be considered as “significant” if  $p < 0.0001$ , “somewhat significant” if  $0.0001 < p < 0.10$  and “not significant” if  $0.10 < p$ .

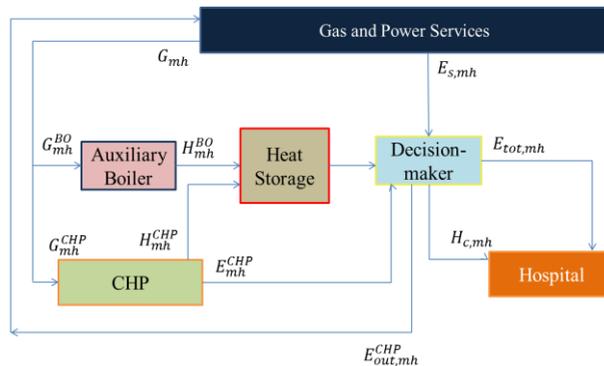
The procedure described this far calculates the so-called *main effect* of parameter, i.e. the effect of each parameter on the objective function. However, to study how the different values of the parameters affect the objective function, it is advisable to enlarge the mere analysis of the main effects by evaluating the *interaction effects*. The interaction effect measures the effect of a parameter on the objective function by varying the possible values

assumed by the other parameters. To investigate the interaction effects on the objective function, the procedure follows the same steps described from Eq.(23) to Eq.(27).

### 3 Case study

The presented mixed-integer linear optimization model has been tested for a CHP located within a microgrid and serving a hospital, as schematized in Fig.1. The hospital is located in South Italy and accommodates about 300 inpatients. Other operation hypotheses of the system are:

- the time horizon is equal to one year;
- the time unit is equal to one hour;
- the costs of gas and electricity as well as price of electricity are known a-priori;
- electrical, cooling and thermal demands per hour during the entire simulated year are known;
- consumption data related to each month have been edited as a typical day, each hourly consumption being equal to the average value computed over 30 daily observations for the same time interval; thus, the edited time horizon holds 12 typical days;
- the hourly demand of both thermal and electrical energy has to be fully satisfied;
- the auxiliary boiler and the CHP system can be switched on or off during a hour.



**Fig. 1.** Energy flows for the considered micro-grid

The micro-grid connected to a hospital consists of a CHP and is equipped with heat storage and an auxiliary boiler. The CHP consumes natural gas and cogenerates electricity  $E_{mh}^{CHP}$  and the thermal energy  $H_{mh}^{CHP}$ . The produced electricity is managed by a decision-maker that evaluates the electrical energy to be used for the satisfaction of the electrical demand of the hospital  $E_{tot,mh}$  and the eventual amount to be sold to the gas and power service  $E_{out,mh}^{CHP}$ . The electricity demand of the hospital  $E_{tot,mh}$  includes electricity and cooling loads; it is the sum of the electricity deriving from the CHP (and not sold) and the eventual amount  $E_{s,mh}$  deriving from the gas and power service. The thermal demand of the hospital is satisfied by the heat produced from the CHP and/or from the auxiliary boiler  $H_{mh}^{BO}$ . The produced heat can be stored in the heat storage if exceeding the thermal demand of the hospital.

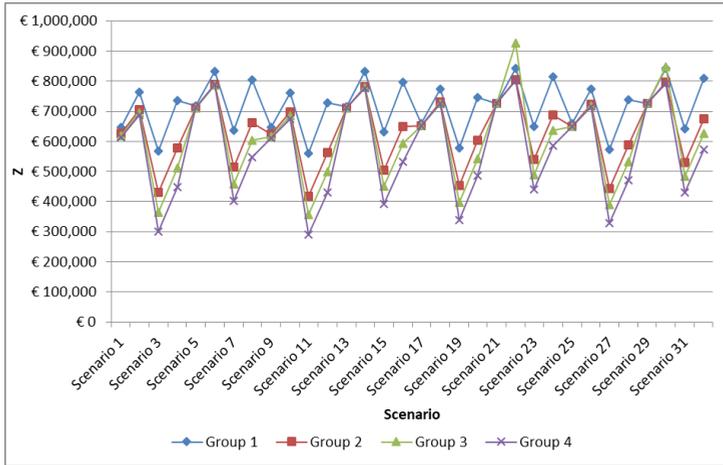
## 4 Results and discussion

Simulations run in order to minimize the total operational costs of a CHP of size  $P_{CHP}$ . The considered parameters are the costs of the imported gas  $C_{u,g}$ , electricity  $C_{u,e}$  and maintenance  $C_{u,man}$  as well as the revenue  $p_{u,e}$  deriving from the exported electricity to the grid and the size of the heat storage  $H_{acc}$ , involved in the analysis as an on/off parameter. In other words, if  $H_{acc} = 0 kWh$  simulations run without considering the presence of the heat storage, otherwise a heat storage of size  $H_{acc} = 750 kWh$  is included. In particular, four CHP power sizes have been simulated at varying the cost and revenue parameters in accordance with a minimum and a maximum value as listed in Table 1. All values have been chosen with respect to the technical and commercial state-of-art [14] and, excepting for  $P_{CHP}$  and  $H_{acc}$ , the remaining terms are expressed in terms of monetary units.

**Table 1.** Values of the parameters involved in the optimization process.

	<b>GROUP 1</b>	<b>GROUP 2</b>	<b>GROUP 3</b>	<b>GROUP 4</b>
$P_{CHP} [kW]$	500	1350	2000	3000
$C_{u,g} [€/Nm^3]$	0.8 – 0.9	0.8 – 0.9	0.8 – 0.9	0.8 – 0.9
$C_{u,e} [€/kWh]$	0.17 – 0.25	0.17 – 0.25	0.17 – 0.25	0.17 – 0.25
$p_{u,e} [€/kWh]$	0.085 – 0.15	0.085 – 0.15	0.085 – 0.15	0.085 – 0.15
$C_{u,man} [€/kWh]$	0.01 – 0.0175	0.01 – 0.0175	0.01 – 0.0175	0.01 – 0.0175
$H_{acc} [kWh]$	0 – 750	0 – 750	0 – 750	0 – 750

The combination of all design parameters yields  $1 \times 2^5 = 32$  experimental scenarios for each group. The model has been solved in the LINGO environment [24] and the optimized results related to the scenarios of each group are reported in Fig.2. From the analysis of the results, the best scenario for each group and the best group for each scenario can be derived. For the best scenario, the sole varying parameter is the power size of the CHP  $P_{CHP}$ , whilst the other parameters assume all the time the same values, in particular:  $C_{u,g} = 0.8 [€/m^3]$ ,  $C_{u,e} = 0.1 [€/kWh]$ ,  $p_{u,e} = 0.15 [€/kWh]$ ,  $C_{u,man} = 0.01 [€/kWh]$  and  $H_{acc} = 750 [kWh]$ . This result, at a first glance, allows assuming that the power size of the CHP is the most influencing parameter affecting the minimization of the objective function. However, when referring to the best group each scenario, in 24 scenarios, out of the total 32 available, group 4 guarantees the minimum of the total operational costs. Concerning the remaining eight scenarios, better results have been achieved for group 2 and for group 3. Nevertheless, even in these cases, the sole parameter that differs when scenarios are fixed is the power of the CHP. Therefore, the power of the CHP seems to be once again the most influencing parameter, but anyway the best size of the CHP cannot be easily identified. The minimized objective functions numerically reported in Fig.2 are illustrated in Fig.3 at varying the operating scenarios.



**Fig. 2.** Comparison among the groups at varying the operating scenarios

The trends of Fig.2 confirm that the power size of group 4 minimizes the total operational costs for most scenarios. Moreover, it is worth noting that the curves, independently of the group to which they belong, are characterized by a marked fluctuation. This reflects the fact that there are other parameters, beyond the CHP power size, influencing the minimization of the total operational cost.

Therefore, the influence of each design parameter on the results needs to be further clarified. To the purpose, the ANOVA test is performed. The design parameters taken into consideration to determine whether they influence or not the results of the objective function are the same reported in Table 1. The analysis is carried out using Design Expert [25] and is supported by  $32 \times 4 = 128$  distinct scenarios, i.e. the 32 identified scenarios repeated for the four groups. As a primarily analysis, Table 2 reports the main effects of parameters.

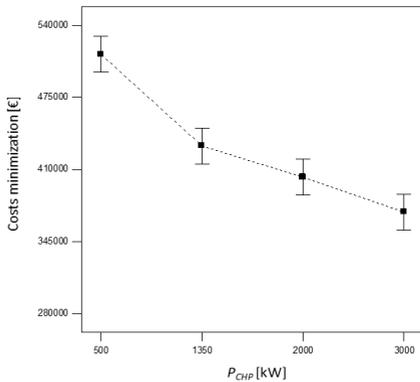
**Table 2.** ANOVA: main effects of the parameters.

<b>ANOVA table main effects</b>			
<i>Source</i>	<i>F-value</i>	<i>p-value Prob&gt;F</i>	<i>Result</i>
$P_{CHP}$	55.26167071	<0.0001	significant
$C_{u,e}$	205.9257419	<0.0001	significant
$C_{u,g}$	106.7201043	<0.0001	significant
$p_{u,e}$	471.5090135	<0.0001	significant
$C_{u,man}$	8.967639577	0.0033	somewhat significant
$H_{acc}$	0.596621292	0.4414	not significant

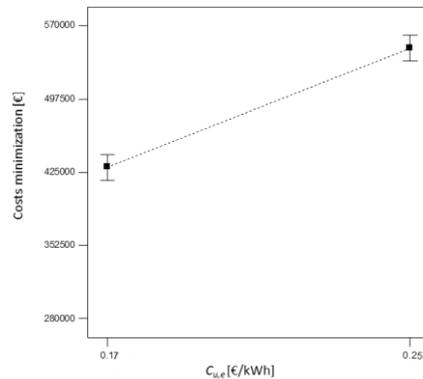
In order to determine the significance of the parameters, the  $F$ -value and the  $p$ -value are compared. As introduced, the effect of the parameter is “significant” if  $p < 0.0001$ , “somewhat significant” if  $0.0001 < p < 0.10$  and “not significant” if  $0.10 < p$ . According to this convention, the power  $P_{CHP}$  of the CHP, the unit cost of electricity  $C_{u,e}$ , the unit cost of natural gas  $C_{u,g}$  and the unit price of electrical energy  $p_{u,e}$  are significant parameters. The unit cost of maintenance  $C_{u,man}$  is somewhat significant, whilst the capacity of the heat storage  $H_{acc}$  is not significant. This result can be affected by the fact that the presence or not of the heat storage does not depend on costs elements, rather it is involved in the analysis with respect to the economic impact in relation to other factors (costs of both electricity and natural gas and price of electricity). Beyond the examination of the significance of

parameters, the results of the ANOVA permit also the ranking of the parameters from the most to the less significant on the ground of the  $F$ -value. In particular, higher values mean higher significance. Therefore, it may be inferred that  $p_{u,e}$  is largely the most influencing parameter followed by  $C_{u,e}$ ,  $C_{u,g}$  and  $P_{CHP}$ .

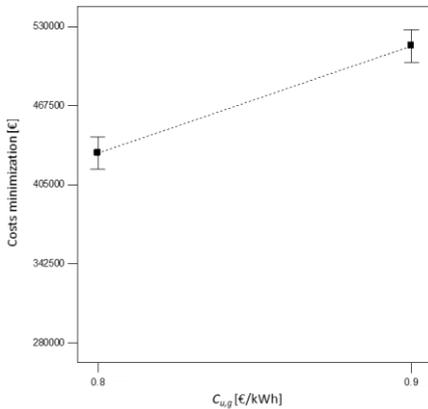
To show the significance of each design parameter, as established through the ANOVA, the main effect plots of Fig.4 are introduced. A main effects plot visualizes the average result of the objective function for each value of the plotted parameter (in the x-axis) considering as if the remaining parameters had no influence on the objective function. Generally, the more inclined is the line the more significant is the parameter. Consequently, a line parallel to the x-axis indicates no main effect.



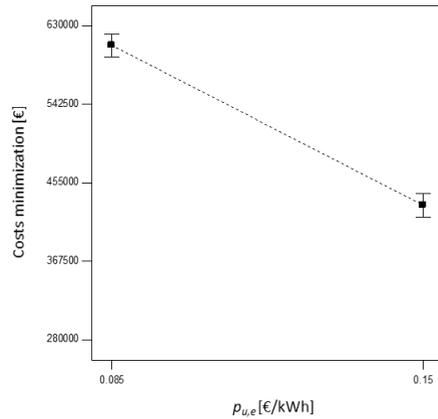
(a)



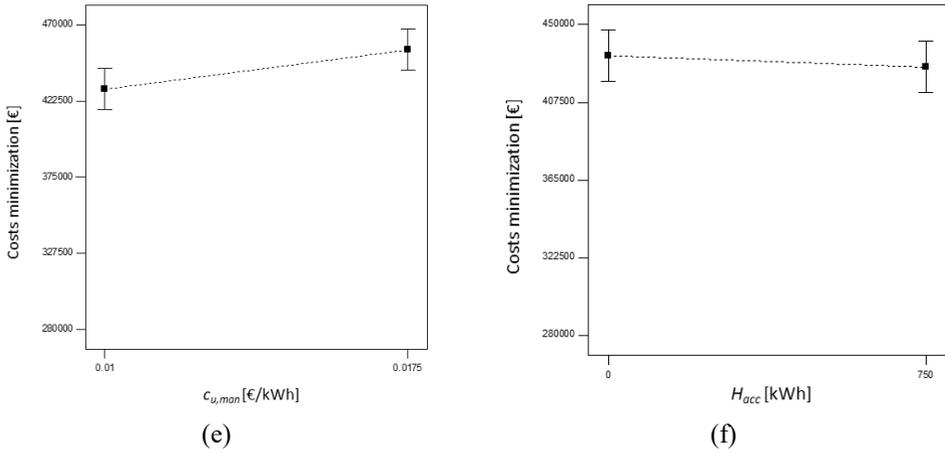
(b)



(c)



(d)



**Fig. 3.** Main effect plot of the: (a) power size of the CHP  $P_{CHP}$ ; (b) unit cost of electricity  $C_{u,e}$ ; (c) unit cost of natural gas  $C_{u,g}$ ; (d) unit price of electricity  $p_{u,e}$ ; (e) unit cost of maintenance  $C_{u,man}$ ; (f) heat storage  $H_{acc}$

Fig.3(a) shows the main effect of the power size of the CHP  $P_{CHP}$  on the objective function. The high slope of the line confirms the significance of this parameter. In other words, the objective function is influenced by the variation of the value of the power size of the CHP. As regard to the unit cost of electricity  $C_{u,e}$  in Fig.3(b), the unit cost of natural gas  $C_{u,g}$  in Fig.3(c) and the unit price of electricity  $p_{u,e}$  in Fig.3(d), the slope of each parameter indicates, once again, high significance. Finally, the unit cost of maintenance  $C_{u,man}$  plotted in Fig.3(e) is somewhat significant, whilst the non-significance of the heat storage  $H_{acc}$  is clearly evaluable from the graph of Fig.3(f). Indeed, in this last figure, the almost nil slope constitutes the evidence of the fact that the capacity of the heat storage does not contribute in any way to the minimization of the objective function, i.e. to the minimization of the total operation costs. However, it has to be specified that the non-significance of the heat storage is assured for this specific case study and may not be considered as a general conclusion.

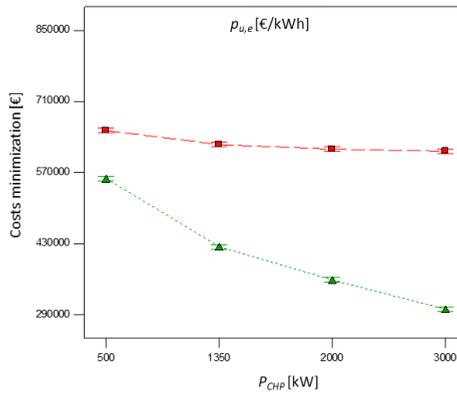
After testing the significance of each parameter, it is reasonable to proceed with the evaluation of the interaction effects as reported in the ANOVA of Table 3. As a remark, this analysis permits to evaluate if the effect that one parameter has on the objective function depends on the values assumed by the other parameters. The heat storage has been eliminated from the analysis, being its main effect not significant.

**Table 3.** ANOVA including interaction for significant parameters

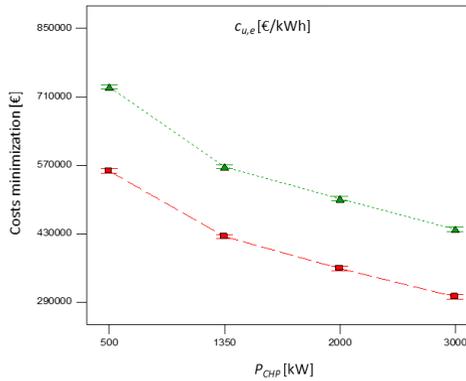
<b>ANOVA table - main and interaction effects</b>			
<i>Source</i>	<i>F-value</i>	<i>p-value Prob&gt;F</i>	<i>Result</i>
$P_{CHP}$	2340.793	<0.0001	significant
$C_{u,e}$	8722.674	<0.0001	significant
$C_{u,g}$	4520.487	<0.0001	significant
$p_{u,e}$	19972.34	<0.0001	significant
$C_{u,man}$	379.8544	<0.0001	significant
$P_{CHP} - C_{u,e}$	38.19779	<0.0001	significant
$P_{CHP} - C_{u,g}$	20.84479	<0.0001	significant
$P_{CHP} - p_{u,e}$	1349.41	<0.0001	significant
$P_{CHP} - C_{u,man}$	16.03949	<0.0001	significant

$C_{u,e} - C_{u,g}$	0.506471	0.4783	not significant
$C_{u,e} - p_{u,e}$	677.6341	<0.0001	significant
$C_{u,e} - C_{u,man}$	0.506366	0.4783	not significant
$C_{u,g} - p_{u,e}$	3.931023	0.0501	not significant
$C_{u,g} - C_{u,man}$	3.930827	0.0501	not significant
$p_{u,e} - C_{u,man}$	3.930729	0.0501	not significant

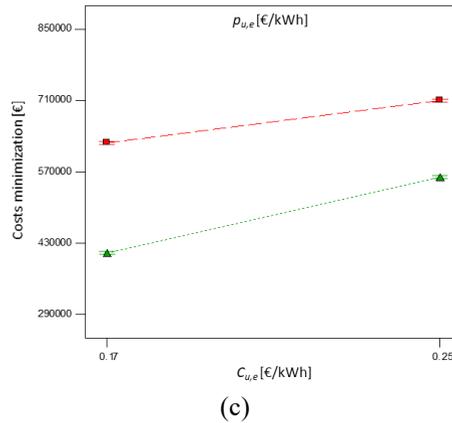
As can be seen from Table 3, the effects of the parameters have been recalculated to consider interactions. To the purpose, each possible combination between two parameters has been considered and the  $F$ -value and the  $p$ -value have been compared to evaluate significance. It comes clearly out that each interaction involving the power size of the CHP is significant, being the most relevant interaction is  $P_{CHP} - p_{u,e}$ , followed by the interactions involving the unit cost of electricity  $C_{u,e}$ , the unit cost of natural gas  $C_{u,g}$  and the unit cost of maintenance  $C_{u,man}$ . Another significant interaction is  $C_{u,e} - p_{u,e}$ , whilst the interaction  $C_{u,e} - C_{u,g}$  is non-significant, although the unit cost of natural gas and the unit cost of electricity are both significant parameters. The graphical representation of the interactions is presented in the interaction plots of Fig.4.



(a)



(b)



**Fig. 4.** Interaction plots for: (a)  $P_{CHP} - p_{u,e}$ ; (b)  $P_{CHP} - C_{u,e}$ ; (c)  $C_{u,e} - p_{u,e}$

In the interaction plots, parallel lines indicate low effect of the interaction, whilst the greater is the difference between the lines the higher is the effect of the interaction. Having said this, the significant difference in the slopes of Fig.4(a) confirms that the high impact of interaction  $P_{CHP} - p_{u,e}$  on the objective function. Fig.4(b) reports the interaction plot for  $P_{CHP} - C_{u,e}$ . In this case, the interaction is less significant if compared with the previous (as also noticeable from its corresponding low  $F$ -value in Table 3). Finally, the effect of the interaction  $C_{u,e} - p_{u,e}$  is reported in Fig.4(c).

## 5 Conclusions

In this paper, a mixed-integer linear programming model for the optimal operation strategy of a CHP system equipped with heat storage and an auxiliary boiler is considered. Different operating scenarios are simulated in order to minimize the total operational costs of the system. In addition, an ANOVA test is pursued in order to comprehend which design parameters affect the minimization.

The model has been applied to a case study consisting of a CHP within a hospital accommodating 300 patients. Scenarios at varying the power size of the CHP, the unit costs of electricity, natural gas and maintenance, the unit price of electricity and the capacity of the heat storage have been taken into consideration and optimized. Successively, the ANOVA test has been carried out to analyse how each aforementioned design parameter impacts on the minimization of the total operational costs.

Results identify the power size of the system, the unit costs of natural gas and electricity and the unit price of electricity as the most significant parameters that need to be taken into consideration when dealing with the operation strategy of a CHP. Moreover, interactions between the power size of the CHP and both the unit cost and the unit price of electricity and the interaction between the unit cost of electricity and the unit price of electricity are highly significant. Surprisingly, the presence of the heat storage does not affect the results in terms of minimization of the total operational costs.

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