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Procedure to obtain the optimal distribution cooling capacity of an air-condensed chiller plant for a hotel facility conceptual design

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Abstract

The article presents a novel methodology for designing chiller plants for a hotel facility to determine the optimal distribution of the chillers cooling capacity that compose the plant. The methodology proposes three phases. In the first, the statistical analysis allowed to determine the cooling demand required in the facility, where the constructed thermal demand profiles reflect future operating conditions, and to obtain the individual cooling capacities of the chillers. In the second phase, the black box models were built to simulate the chillers energy performance and, using a mathematical algorithm allows to obtain a combination of chiller plants. The third phase constitutes the energy evaluation through the solution of a mathematical optimization problem and using a genetic algorithm. This was carried out under the sequence approach and the optimal load of each machine against the working conditions. This analysis allows calculating the performance, the life cycle cost, and the indirect environmental impact. The paper proposes a case study to demonstrate the feasibility of applying the methodology to the initial design stage, achieving a saving of 14,4%. Finally, using statistical analysis, the method allows comparing the relationship between each chiller plant considering the design and operating parameters.

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Keywords: Genetic algorithm; Chiller plant; Cooling capacity; Optimal chiller loading and sequence; Hotel facilities

1. Introduction

A cooling plant is a system with the highest energy consumption in a hotel facility, reaching that tropical hotel facilities climates up to 60% of total consumption [1]. The design starts with the process necessary to determine

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Nomenclature

a_0, a_1, a_2	Correlation coefficients of the black box model of electrical power.
BLR	Building Load Ratio
C_I	Specific Consumption Index
CL_i	Building cooling load for each interval of time i (kW).
CL_{peak}	Building Cooling Load Peak (kW).
Comb	Combinations of chiller plant
COP	Coefficient of performance
Cp	Heat capacity of water at 7 °C (kJ/Kg°C).
$E_{annualcost}$	Annual cost of electricity for each plant ($ annual).
$E_{cost,i}$	Cost of electrical energy consumption of each chiller plant in (k_i)
Electric tariff	Price of the electricity tariff according to local regulations ($/kWh).
Ek	Electrical energy consumption of each chiller plant in (k_i).
E_{ki}	Electrical energy consumption of each chiller plant in (k_i) (kWh).
ε	Emission index ($kgCO_2$/kWh).
$F\varepsilon$	Emissions index factor for local electricity generation subject to a specific fuel
fi	Absolute frequency of the score.
Fi	Cumulative frequency up to the lower limit of the score.
GA	Genetic Algorithm.
Hdo	Occupied Room Indicator
H_z	Set of histograms with different z value.
IC_{plant}	Initial cost of a chiller plant ($).
IC_0	Initial cost of a reference chiller ($).
IP	Indirect environmental impact caused by the pollution (CO_2/kWh).
J	Percent of Percentile Cases (%).
k_i	Simulation scenario.
LCC	Life cycle cost ($).
Li	Lower score limit.
Ls	Upper Score limit
MC_n	Chiller maintenance cost ($).
MC_{plant}	Chiller plant maintenance cost ($).
$\dot{m}_i$	Chiller water mass flow (kg/s).
n	Sample size.
n_{ch}	Total of chiller selected in each chiller plant
N	Chiller plant lifetime (years).
Nc	Total of commercial chiller
Ni	Chiller plant feasible combinations
OC	Operating cost ($).
OCL	Optimal chiller loading
OCS	Optimal chiller sequence
Pch	Power consumption of chiller (kW).
PLR	Partial load ratio.
PVF	Present Value Factor
$P_{83,33}$	Percentile value that represents the 5/6 sextile in the range of data.

Qch	Cooling load for the chiller (kW).
Qcl	Total cooling load (kW)
Qch_n	Cooling capacity of the chiller at standard conditions according to manufacturer (kW)
Qch_o	Cooling capacity of the reference chiller (kW)
$Qch_{theoric}$	Theoretical chiller cooling capacity.
r	Discount rate (%).
SF	Safety factor.
Sj_{off}	Stage off threshold
Sj_{on}	Stage on threshold
T	Year in which the annual cost is determined (year).
$Tcair,in$	Condenser air inlet temperature (°C).
$Tchw,s$	Chiller water supply temperature (°C).
$Tchw,r$	Chiller water return temperature (°C).
μ	Balancing factor for maintenance costs.
xi	Average value of the predominant class.
x_0, x_1, x_2	Correlation coefficients of the black box model of nominal cooling capacity.
z	Bins classification.

Subscripts

ch	Chiller water
i	Ith
max	Maximum
min	Minimum
c	Condenser
in	Inlet
s	Supply
r	Return
peak	Peak
theoric	Theoric

the cooling capacity of the system and its configuration. This allows to select type, number of chillers, hydraulic arrangement, load distribution. According to Ji-Hye et al. [2]; Wang et al. [3]. A hotel facility has great diversity of cooling loads and the system operates under partial load for a considerable part of its operating time. For this type of construction, a correct determination of these elements is an important issue to establish the energy efficiency fora hotel facility, the variability of consumption can reach values up to 69% [4].

The application of symmetrical or asymmetrical configurations describes the nominal load distribution; The major advantage of the symmetrical arrangement is the ease of maintenance, but its configuration causes lower efficiency levels when it works with partial loads. An asymmetric configuration allows an efficient adjustment of the system to variations in thermal load, which represents a potential savings around 10.1% compared with a symmetric plant [5].

Nowadays, the cooling capacity distribution among chillers considers recommendations or standards. Cuban standard NC-220:2009 divide the total cooling capacity by the number of chillers installed, which according to Torres et al. [6], it implies a symmetrical system design. The ASHRAE standard 90.1–2013 [7], through table G 3.1.3.7, also recommends the use of symmetrical chillers and Chan et al. [8] proposes as a general rule for facilities with a cooling demand between 1050 to 7032 kW should use four to eight symmetrical chillers.

According to Taylor [9], the number of chillers, and the distribution of their cooling capacity, should depend on the characteristics and frequency distribution of the cooling loads in the facility; in a building with a large load variation, designers recommend using several chillers of different capacities. In case of a constant load, designers can use a small or large capacity chiller. However, in [9] does not propose the distribution of the capacity. A study developed by Bitondo and Tosí [10] proposes the use of three chillers to support load distribution capacity (first chiller: 40%, second chiller: 40%, third chiller 20%). Haviland [11] recommend configurations composed of two chillers, one with 40% of the load and the other with the remaining 60%, under the criterion that, in these applications, refrigeration plants can spend over 50% of their time working under the partial load regime. Mathew and Greenberg [12] suggest a proportion of 30% and 70% for laboratories. Stanford III [13] recommends using configurations between 80% to 20% of its total capacity. A common problem in the studies is that these recommendations do not reflect a structured methodology and the energy analysis that supports the decision.

There are few studies in which authors evaluate some specific configurations. Yu and Chan [14] using the software TRNSYS compared the energy efficiency of four configurations based on a set of chiller part load performance curves considering a thermodynamic chiller model. The 1st and 2nd configuration are a distribution of six to eight symmetrical chillers respectively, while the 3rd configuration presents an arrangement of four symmetrical chillers with 19% of total cooling capacity each and two with 12%. Six chillers distributed in three symmetrical pairs of 21%, 17% and 12% of the total capacity form 4th configuration. Also, the 3rd and 4th configurations provide energy savings of 8.9% and 9.1% respectively, compared to the 1st configuration. Gang et al. [4] analyze the energy performance of two configurations, the first one included seven symmetrical chillers and the second one had five symmetric chillers with 16% of the total capacity each one of 8%. The results showed a saving of 1.6% of 2nd configuration compared to 1st configuration.

Recent studies, conducted by Gang et al. [15,16]; Cheng et al. [17]; Kang et al. [18]; Cheng et al. [19]; Huang et al. [20] and Li et al. [21], determine the nominal capacity of each chiller, balancing the nominal cooling loads in a range of 10% of the total system load. Shiming [22] recommends statistical analysis to determine individual chillers capacity considering the frequency distribution of the cooling loads. Also, this author considers that the capacity of each chiller should coincide with the load values with the highest percentage of frequency but does not apply an optimization procedure or an algorithm that guarantees an accurate result.

Considering the aspects to improve in a chiller plant design, this paper proposes a methodology to design a chiller plant adjusted to various scenarios in a hotel facility, ensuring a minimum energy consumption. The methodology integrates the procedure to generate alternatives for chiller plant configurations with different cooling capacity distributions, the energy evaluation and selection of the optimal distribution cooling capacity in the chiller plant. The chiller plant performance configurations were tested under building load demand and optimization problem to determine the best alternative; this selection is achieved by solving the problem of Optimal Chiller Loading (OCL) and Optimal Chiller Sequence (OCS) using meta-heuristic methods. The methodology includes the Life Cycle Cost (LCC) analysis for each proposed configuration and the indirect environmental impact.

2. Materials and methods

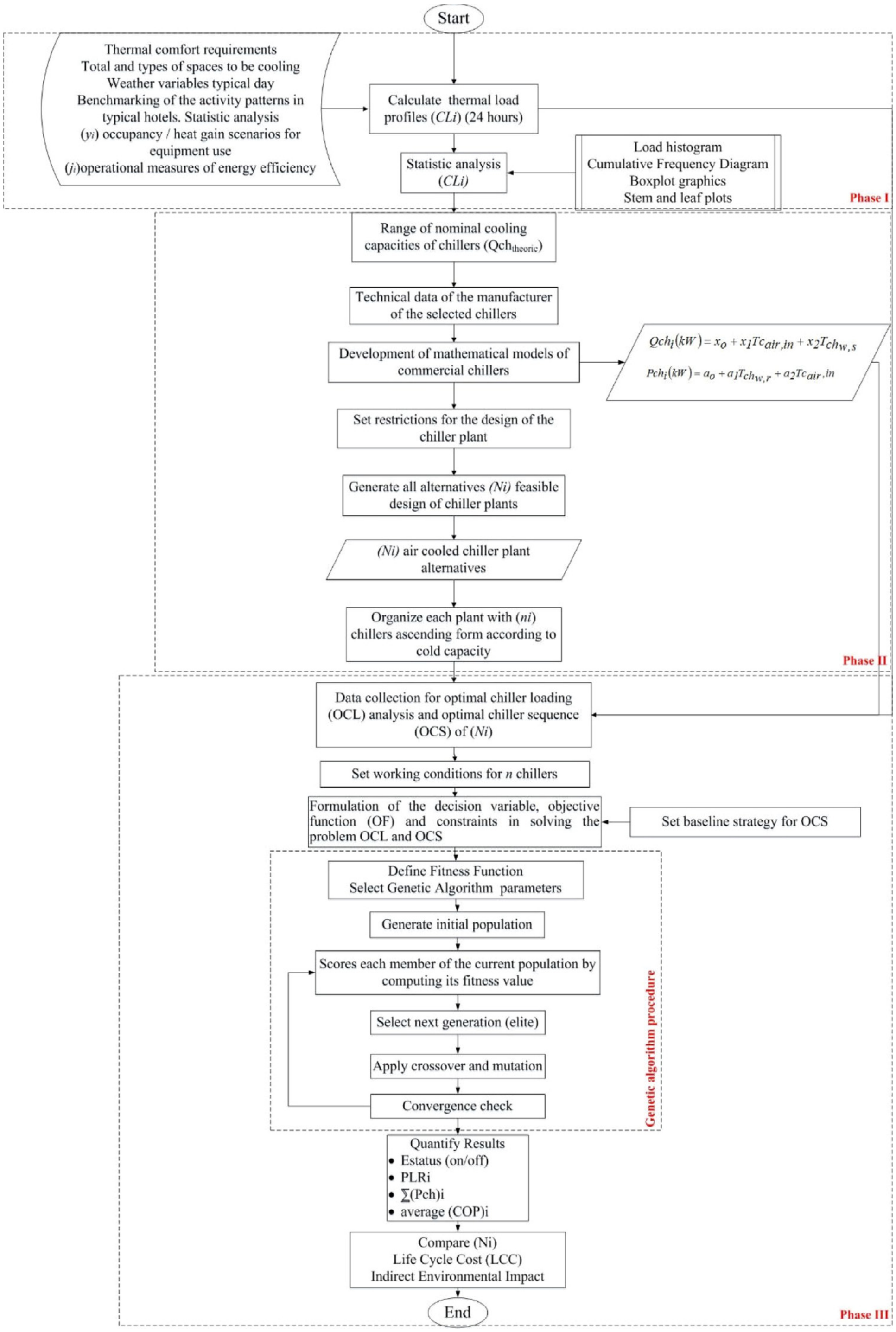
2.1. Methodology to determine the optimal distribution of the cooling capacity of a chiller plant for a hotel facility

The methodology considers that the chiller plant is a decoupled system, composed of n air-cooled chillers arranged in parallel. The methodology will only apply to the primary circuit because the influence of the secondary circuit is negligible in the total consumption [20,23,24]. The methodology is divided into three fundamental phases: Statistical analysis of cooling demand profiles (Phase I), chiller plant configuration (Phase II), and energy performance optimization (Phase III). Fig. 1 describes the heuristic diagram of the procedure.

2.1.1. Phase I. Statistical analysis of cooling load profiles.

The [25] recommend to calculates the thermal cooling construction demand profiles in hotels based on comfort design conditions, weather, heat gains scenarios for activities levels, infiltration, and ventilation load. Several available programs that use the transfer unit method or the time series method such as TRNSYS or Energy-Plus carry out this analysis. For its preparation, some aspect regard to comfort condition and occupational activities schedules consider the following aspects:

- The hotel facility comprises three functional areas: rooms, public areas (lobby, restaurants, shops, gym, cabaret, swimming pool, among others) and service areas (kitchen, laundry, administrative offices, machine room, among others). This feature facilitates the creation of multiple thermal zones in the building, having each one different from the comfort conditions and work schedules [26].



$$Qch_i(kW) = x_o + x_1 Tc_{air,in} + x_2 T_{ch_{w,s}}$$

$$Pch_i(kW) = a_o + a_1 T_{ch_{w,r}} + a_2 Tc_{air,in}$$

Fig. 1. Heuristic diagram of the procedure to determine the optimal distribution of the cooling capacity of a chiller plant for a hotel facility.

- The first load profile must correspond with the deterministic analysis of the cooling demand, considering the worst scenario registered with critical meteorological variables and a hotel with fully occupancy scenario. This load profile provides the total chiller plant capacity.

- The services and activities provided in a hotel can vary in a temporary space of 24 h and should be considered during the design phase, for example: conferences, banquets, cabaret, restaurant services, day services with specific activities, among others. From these assumptions, several thermal demand profiles during installation must be constructed and use statistical information gathered from similar hotels in the same region to:
  - ✓ To simulate different occupancy rates in the functional area (rooms and public areas).
  - ✓ To implement energy efficiency measures regarding to the occupancy rate, to establish the selective occupation and prioritizing rooms with the lowest thermal demand.
- Tropical hotels, considering factors such as weather and quality service offered for the hotel, consider the unoccupied room, and define a partially charged room searching for comfort conditions to maintain a high level of indoor air quality. Commonly, the management order to staff to establish a set-point in 25 °C.

A database must be built for each Simulation Scenario (k_i), also each interval of time (i) reflects the Building Cooling Load (CL_i). All values will be used in the statistical analysis section. The Building Cooling Load Peak (CL_{ipeak}) on k_i will establish the Total Cooling Load (Qcl) considering, in addition, its increase with the use of a Safety Factor (SF). This will be the first restriction of the system, according to Eq. (1).

$$Qcl = SF * CL_{peak}, \quad 1.1 \leq SF \leq 1.2 \tag{1}$$

The major purpose of this phase is to examine, using the means descriptive techniques, the behavior of the thermal profiles and find patterns of use that lead to establish the nominal capacity of the chillers with statistical tools such as the frequency histogram, the cumulative frequency chart, boxplot chart and stem-and-leaf plots. In the histograms technique does not exist a universal method that precisely determines the number of bins for a study, causing each technique to provide different amplitudes in each class and, therefore, different results. In this research, it is considered the Lapin [27] criteria that refers, that one way to decide the number of classes in a histogram is to convert it into an iterative process and select the one that obtains a logical explanation. Therefore, considering the heterogeneity of criteria in the selection of the histogram rules and the results of a previous investigation carried out by Correia and Diaz [28], an iterative process considering the sample size (n) of (CL_i) is carried out. This statistical procedure allows to identify the predominant (CL_i) in all simulation scenarios built (k_i):

Step 1. To construct Histograms (H_z), using Eq. (2) allow to evaluate each H_z in the set of possible class bins (z).

$$H_z = \begin{cases} \sqrt[3]{n} \leq z \leq & for\ n < 100\ z_{max} = 2 * \sqrt{n}\ n, k \in N \\ & for\ n \geq 100\ z_{max} = 10 * \log n \end{cases} \tag{2}$$

Step 2. To determine the predominant class values for the selection of nominal cooling capacities. This value is obtained by constructing a box-plot chart with the absolute frequency values of each histogram. Eq. (3) defines the predominant classes.

$$predominant\ class\ (x_i) \geq P_{83.33} = L_i + \frac{1}{f_i}\left(\frac{Jn}{100} - F_i\right) \tag{3}$$

Where the P83.33 percentile value represents the 5/6 sextile in the data range.

Step 3. To determine the midpoint of the class (xi) of the predominant classes selected. This value establishes the Theoretical Chiller Cooling Capacity ($Qch_{theoric}$) observed in Eq. (4).

$$Qch_{theoric} = xi = \frac{(Ls + Li)\, i}{2} \tag{4}$$

The value of ($Qch_{theoric}$) is compared with values of commercial chiller cooling capacities as is set in Eq. (5).

$$Qch_n =\approx Qch_{theoric} \tag{5}$$

The Qch_n is the cooling capacity of the chiller at standard conditions according manufacturer selected. Datasheet information of these selected chillers will prepare the mathematical models that describe the variables: Cooling Load for the chiller (Qch) and Power Consumption of chiller (Pch).

2.1.2. Phase II. All chiller plant alternatives configuration generated according to design constraints.

This phase generates all alternatives subjected to design constraints divided into two steps: the first one is the mathematical black box model construction from datasheet of the selected chillers, and the second step is the generation of chiller plant configurations using a mathematical factorial algorithm.

Step 1: Construction of black box-type mathematical models for selected chillers

These mathematical models will be built applying the generalized least-squares method and using the black box type mathematical model methodology for the construction and selection [29]. A multiple linear regression model is selected for the energy simulation. The Cooling Capacity (Qch_i) is a function of the following independent variables, Eq. (6) shows this relation.

$$Qch_i\,(\text{kW}) = x_o + x_1 Tc_{air,in} + x_2 T_{chw,s} \quad x_j \in Q, j = [0, 1, 2]\,, Tc_{air,in} f\,(Tamb) \tag{6}$$

For the case of the ($P_{ch,i}$), it is decided that the independent variables are those that can be operationally modified, the ($Q_{ch,i}$) is implicit and there is no collinearity between the variables, so the mathematical model takes the form of Eq. (7).

$$Pch_i\,(\text{kW}) = a_o + a_1 T_{chw,r} + a_2 Tc_{air} \quad a_j \in Q,_i = [0, 1, 2]\,, Tc_{air,in}, T_{chw,r} \in Q \tag{7}$$

Where, $T_{chw,r}$ represents the chilled Water Return Temperature and its given by Eq. (8)

$$T_{chw,r}\,(^\circ\text{C}) = \left(\frac{CL_i}{\dot{m}_i Cp} + T_{chw,s}\right) \tag{8}$$

Step 2: Chiller plant configurations

The generation of alternatives will be subject to constraints that are established by designers such as the limit of (n) chillers that compose the plant and the total capacity of the system. To accomplish this step, designers must carry out a mathematical algorithm to evaluate all combinations that meet all constraints showed in the below procedure:

1. From several commercial chillers obtained in Phase 1, defined with variable (N) and the number of chillers (n_{ch}) desired in each configuration. Eq. (9) shows the number of Possible Chiller Plant Combinations ($Comb$).

$$Comb = \frac{(Nc)!}{n_{ch}!\,(Nc-1)!} \tag{9}$$

2. It is important to restrict the number of possible combinations to those that are feasible (Ni), they must meet the following constrains:

$$Ni = \left(\sum_{j=1}^{n_{ch}} Qch_n\right) \; subject\ to \quad Qcl = SF * CL_{peak}, \quad 1.1 \le SF \le 1.2 \tag{10}$$

Finally, the last result of this phase is to obtain all possible chiller plants combinations composed by the chillers with the selected individual capacities.

2.1.3. Phase III. Energy analysis of chiller plants by solving an OCL and OCS control problem.

The third phase considers the possibility that the plant has more than one chiller and may have symmetrical or asymmetric configuration regarding their cold capacity, as well as a different electrical demand.

There are four OCS strategies: (1) bypass flow-based sequencing control, (2) return chilled water temperature-based sequencing control, (3) direct power-based sequencing control and (4) total cooling load-based sequencing control. According to Sun et al. [30], the best approach is the total cooling load-based sequencing control because the other methods employ indirect indicators related to the thermal load, which implies that they are not proportional to it. However, in [31] revealed that this strategy has several limitations. For example, it does not guarantee an optimal distribution and all chillers in operation may be inappropriate. For that reason, the combination of the sequence based on the load with other approaches can improve the results. To ensure optimal results, the method propose the use of a baseline that combines direct power-based sequencing control and total cooling load-based sequencing control as is shown in Fig. 2. The chillers are arranged from lowest to highest according to their individual cooling capacity, defined by the variable (Qch_i).

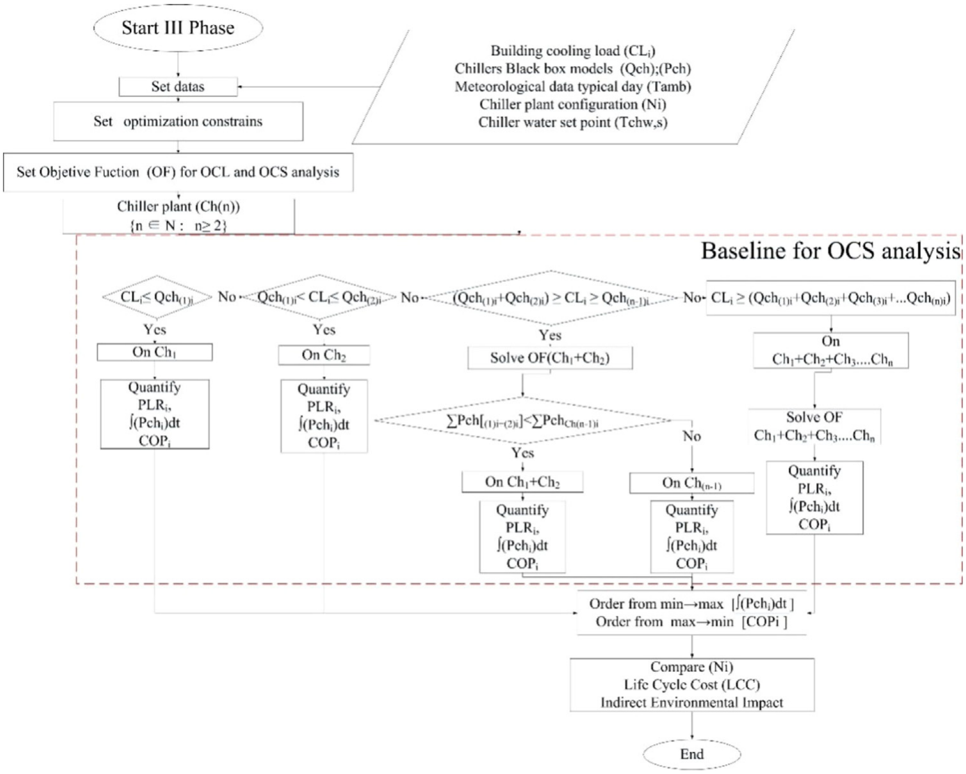


Fig. 2. Baseline schedule of OSC strategy.

2.1.4. *Formulation of the decision variable objective function and constraints in solving the problem OLC and OCS*

The purpose of the optimization problem is to reduce the electricity consumption of the chiller plant and, simultaneously, maintain the comfort levels in the hotel facility. As an initial stage, the system (chiller plant) is decoupled, to only analyze the direct interaction between the chiller plant and the thermal demand of the building. The OCL problem to be solved is classified as a non-linear optimization problem with restrictions and a combinatorial optimization problem with continuous, discrete, and binary variables. The Eq. (11) defines the objective function and Eq. (12) to (15) define constraints.

ObjectiveFunction:

$$\min_{PLR}\left\{\left(\sum_{j=1}^{n}\left(a_0+a_1\left(\frac{CL_i PLR_i}{\dot{m}_i Cp}+T_{chw,s}\right)+a_2 Tc_{air}\right)\right)\right.$$
$$\left.+\left(\left|Q_{ch,max}-\sum_{j=1}^{n}\left(Qch_{i,n} PLR_i\right)\right|\right)+\left(\frac{n}{\sum_{j=1}^{n} COP}\right)\right\}\cdot s_j \tag{11}$$

Subject to

$$CL_i\,(\text{kW}) \le \sum_{k=1}^{n}\left(Qch_i * PLR_i\right)(\text{kW}) \quad n \in N\ \forall, n \ge 2 \tag{12}$$

$$S_j = \begin{cases} if\ \ PLR = 0\ then\ S_j = 0\ \ (off) \\ if\ \ 0 < PLR \le 1\ then\ S_j = 1\ \ (on) \end{cases} \quad Sj \in \{0;1\} \tag{13}$$

$$T_{chw,s}\,(^{\circ}\mathrm{C}) \in N, T_{chw,s} = 7 \ldots 13 \tag{14}$$

$$CL_{(i)}\,(\mathrm{kW}) = \max[CL_{(t-1)}: CL_{(t)}] \quad t \in N, t = 1 \ldots 24 \tag{15}$$

The decision variable ($PLR_{n,i}$) is defined as the Partial Load Coefficient of each chiller and theoretically as shown in Eq. (15):

$$PLR_{n,i} = \frac{CL_i}{Qch_i} \tag{16}$$

The Coefficient of Performance (COP) of each chiller (n) at time interval I it is given by Eq. (17)

$$COP_{i,n} = \frac{Qch_{i,n}PLR}{a_o + a_1\left(\left(\frac{CL_i PLR}{\dot{m}_i Cp} + T_{chw,s}\right)\right) + a_2 Tc_{air}} \tag{17}$$

The variable Sj defines the "on" and "off" interval status analyzed. Eq. (13) describes the restriction referred to the minimum range between the turn on and turn off time to establish that a chiller should not be turned off and suddenly restarted. This constraint prevents damage due to frequent starts and stops. Chang et al. [32] recommends 30 min to an hour as the minimum setting range of time between stops and starts.

Manufacturers suggest that the best performance chiller plant will occur when the sum of the energy consumed by each machine is minimized. For the above mentioned, first there must be satisfied the fundamental premise of satisfying the thermal demand in the facility. The optimal solution for each point of demand analyzed (chiller and proposed combination) will subsequently allow the energy behavior of each analyzed plant against the different simulation scenarios. Finally, the procedure recommends selecting those combinations with the best energy performance compared with all the analyzed load profiles. This measure the adaptability that a system requires. Highlighting, that the solution of an OCL problem gets hard to solve when chillers have different characteristics and cooling capacity. Therefore, the use of artificial intelligence tools to reach accurate solutions is suggested.

2.1.5. Using Genetic Algorithms to solve OCL and OCS problems

The Genetic Algorithm (GA) used to solve the OCL problem, require processing the variables PLR of the chiller unit and the number of units operating in parallel. The initial GA population for the variable (PLR) is constructed using individuals that represent a feasible solution to the problem and constitute a solution vector in the problem space. The code used to represent the PLR values as strings of real variables. Eq. (18) defines the individual k of t generation.

$$\underset{PLR}{\rightarrow}{}^{t} = (PLR_1, PLR_2, \ldots PLR_n) \quad 1 \leq k \tag{18}$$

Where, PLR_n are the genes of the individual and whose alleles (numerical value of each gene) are the values of PLR of each chiller. Fig. 3 shows the population structure.

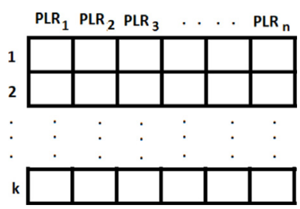


Fig. 3. Population structure showing k individuals with the PLRs of the n combination chillers.

2.1.6. Life cycle cost (LCC) and indirect environmental impact analysis

The solution of the OCL and OCS problem allows obtaining the energy performance of each proposed chiller plant, evaluated in different simulation scenarios (k_i) were ($i = 1 \ldots 24$ h). Eq. (19) shows the Electrical Energy

Consumption of each chiller plant in (k_i):

$$E_{k,i}\,(\text{kWh}) = \sum_{(i=0)}^{(i=24)} Pch_i \tag{19}$$

It is necessary to establish the cost of the electricity tariff for the case study according to local regulations Therefore, the Cost of Electrical Energy Consumption of each chiller plant in various (k_i) ($E_{cost,i}$) is:

$$E_{cost,i}\,(\$) = E_{k,i}\left(Electric_{tariff}\right) \tag{20}$$

The ($E_{cost,i}$) is uniformly distributed over the period of one year, so Eq. (21) describe the Annual Cost of Electricity for each plant.

$$Eannual_{cost}\,(\$) = \sum_{j=1}^{(365/ki)} E_{cost,i} \tag{21}$$

Considering the decoupled system, only the initial cost of the water chillers and their relevant accessories are included in the investment costs. The initial cost (USD \$), for each chiller plant is calculated according to the ex (22) given by Cheng et al. [17]. The initial cost of a reference chiller (IC_0) includes the cost of its main elements (condensing system and pumps).

$$IC_{plant}\,(\$) = \sum_{1}^{n}\left[IC_o * \left(\frac{Qch_n}{Qch_o}\right)^{0.4}\right] \tag{22}$$

The Maintenance Cost (MCn) of the chiller is based on rules established by engineering practices and depending on the (Qch_n), Eq. (23) was exposed by Tredinnick [33].

$$MC_n = Qch_n * MC_n \quad \therefore \; MCn = \left\{\begin{matrix} 6.17\,(\text{US\$/kW}) & (Qch_n < 528\text{ kW}) \\ 4.63\,(\text{US\$/kW}) & (528 \le Qch_n < 1055\text{ kW}) \\ 2.57\,(\text{US\$/kW}) & (Qch_n \ge 1055\text{ kW}) \end{matrix}\right\} \tag{23}$$

Eq. (24) gives the maintenance cost of the chiller plant. Where μ, is an equilibrium factor, equal to 0.8 for plants made up of 2 chillers and 0.7 for plants made up of 3 chillers or systems with more than 3 symmetrical chillers. For the rest of the design options, this factor is not established [20].

$$MC_{plant}\,(\$) = \mu * \sum_{j=1}^{n} MC_n \tag{24}$$

Life Cycle Cost Analysis (LCC) considers the chiller plant lifetime and the consumer discount rate. Eq. (25) shows the LCC relation.

$$LCC\,(\$) = IC + \sum_{t=1}^{N} \frac{OC}{(1+r)^t} \tag{25}$$

The $\sum_{t=1}^{N} \frac{OC}{(1+r)^t}$ term is known as the Present Value Factor (PVF). This can also be given by Eq. (26):

$$PVF = \sum_{t=1}^{N} \frac{OC}{(1+r)^t} = \frac{1}{r}\left[1 - \frac{1}{(1+r)^N}\right] \tag{26}$$

The chiller plants lifetime (N) considered is 25 years, according to literature, Eq. (27) shows the Operating Costs (OC).

$$OC\,(\$) = Eannual_{cost} + MC_{plant} \tag{27}$$

Substituting Eqs. (26) and (27) in Eq. (25), the LCC remains according Eq. (28):

$$LCC\,(\$) = IC + PVF * \left(Eannual_{cost} + MC_{plant}\right) \tag{28}$$

Increasing the energy efficiency of the chiller plant leads to a reduction in the indirect environmental impact. Considering the Specific Consumption Index (C_I) of electricity generation, the Emissions Index Factor for local electricity generation subject to a specific fuel is (F_ε). The Emission Index (ε) is calculated according to Eq. (29):

$$\varepsilon_{\left(\mathrm{kg_{CO_2}/kWh}\right)} = C_I F_\varepsilon \tag{29}$$

Finally, the Indirect Environmental Impact caused by the pollution (IP) derived from the burning of fossil fuels remains according to Eq. (30): Indirect environmental impact caused by the pollution

$$IP\ (\mathrm{kg_{CO_2}/year}) = E_{k,i_{annual}} * \varepsilon \tag{30}$$

Obtaining these indicators will allow the selection of the most efficient water chiller plant for the hotel facility.

3. Study case. Chiller plant for a new hotel

The study case is the design of a new hotel in a tropical climate. It is planned to install a chiller plant to support the following areas: 87 rooms, 2 specialty stores, a restaurant-kitchen, a cabaret and 9 offices. TRNSYS 16 software was used to simulate the different hotel thermal zone. The materials of the main elements, as well as their thermal properties, are obtained from the TRNSYS digital library. The internal heat gains were defined for a specific occupation, depending on the thermal zone, defining the sensible and latent heat gains according to the standard ISO 7730. In addition, the comfort conditions of each thermal zone, the artificial light gains and the different electronic equipment were obtained from the CIBSE guide [34]. Infiltration gains considered a 0,8 factor. The heat gain caused by convection/radiation fraction derived from electronic equipment is 0.3/0.7, respectively. The dimensions of each thermal zone, as well as the definition of surfaces with direct sunlight and heat gains, was considered. A cooling load profile (k1) was generated. The total cooling capacity of the chiller plant is set to 560 kW, and the chiller plant configuration according to the national standard will be a symmetric chiller plant with two 280 kW air-cooled chiller. This configuration will be taken as a reference case. To show the effectiveness of this new methodology, the same study case will be considered.

3.1. Phase I. Statistical analysis of cooling load profiles

In contrast to traditional design standards for chiller plants, the method considered several simulation scenarios, showing the diversity of thermal demand in this type of building. As defined for this phase, operating and occupancy patterns have been taken from research performed by Montelier [35]; Cuza [36]; Díaz et al. [37,38]; Valdivia Nodal et al. [39] in hotels that are in operation and share common characteristics regarding the type of service, construction characteristics and location, allow us to summarize the following characteristics:

- ✓ This is a transit hotel. There is a service interruption between 10:00 am to 4:00 pm.
- ✓ This hotel has served as host in important government events, replacing the transit hotel modality.
- ✓ The store, the cabaret and the restaurant offer non-exclusive services to guests. The offices occupation considered working hours schedules.
- ✓ The Occupied Room Indicator (Hdo) fluctuates according to the tourist season, considering the following levels: low occupancy (Hdo $\leq$ 10%), medium occupancy (45% $\leq$ Hdo $\leq$ 50%); high occupancy (75% $\leq$ Hdo $\leq$ 90%) and hotel fully occupied (Hdo = 100%).

This information allows the construction of various cooling load profiles (k_i) in the functional areas: rooms, public and back to house. In addition, for the (k_i) calculation the design considered:

- ✓ To assume the recommendation given by Udawatta et al. [40] to apply the concept of a room "partially loaded" (unoccupied rooms but conditioned with a temperature of 26 °C).
- ✓ To simulate occupancy rates of 10, 50, 75, and 100% for the hotel in the rooms and public areas.

According to Yang et al. [41] it was eliminated the load diversity through occupancy strategies using the lowest thermal demand rooms. for occupancies of 75% and 50%.

Besides to the k1 that assumes the critical design conditions, other 7 (k_i) were simulated according to the work schedule established. Each one represents a Building Load Ratio (BLR): 31.5%; 40,19%; 42,92%; 46.06%; 62,39%; 75,36%; 89,67% of BLR that simulate different occupation scenarios and activity levels that can occur in the hotel. If all these load profiles are contrasted, the time-varying of cooling loads can be observed for the hotel in 24 h as

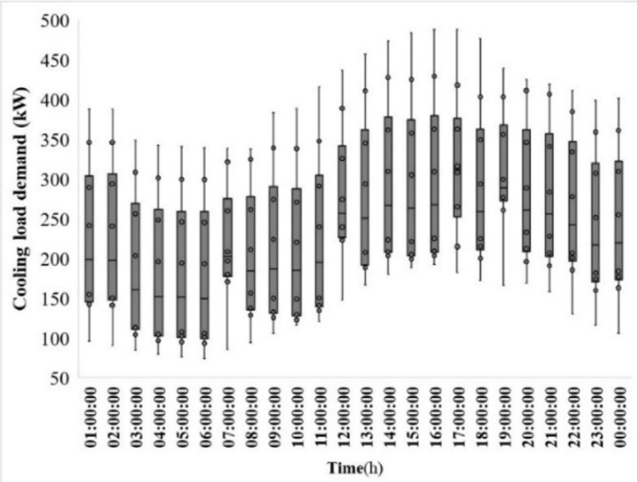


Fig. 4. Variation of thermal demand in a new hotel in a 24 hour period according to feasible scenarios.

shown in Fig. 4. This confirms the marked influence of the building loads dynamics on the operation of the chiller plant.

The statistical analysis allows to obtain the cooling demand values showed in Fig. 4, a sample (n) of 194 values of (CL_i). Histograms were constructed using Statgraphics 18 based on Eq. (2). Eighteen histograms are constructed with the selection of the number of classes from 6 to 23 and an initial value equal to the minimum demand value of 73.67 kW. The box-and-whisker plots is constructed to show the percentile value for each histogram. The mean value of the absolute frequency obtained in Eqs. (3) and (4) defines the selection of the predominant classes used for the construction of the stem-and-leaf diagram. The highest frequency thermal demand values are 100–110 kW, 140–150 kW, 160–170 kW, 200–210 kW and 220 kW. Values between 295–353 kW are included to expand the possibilities of plant configurations. These results are taken as the basis for the selection of the chillers' refrigeration capacities, based on locating commercial chillers with similar capacities based on technical information.

3.2. Phase II. All chiller plant alternatives configuration generated according to design constraints

A total of 11 water chillers are considered for the study. The black box mathematical models using Eqs. (5)–(6) were built to explain the variables (Pch_i) and (Qch_i) based on data from the manufacturer data selected, the mathematical models are evaluated through the method of least squares, applying the regression models, and adjusting data of the measurements using Eviews7 software. Results of the models such as fit capacity, quality of the model, as well as the regression coefficients were set.

The first restriction imposed on the plant is the total number of chillers in the system. This value will depend on factors such as space established for the machine room, budget for investment, availability of equipment, among others. For this case study, the design department selected 2 chillers. The second restriction is given by the SF used, for which a SF is used as recommended by the ASHRAE between 10%–20% of the total installed capacity. Using the mathematical algorithm shown in the step 2 and the mathematical model (5) evaluated with the regression coefficients, counting with a total of 6 combinations. Table 1 summarizes the configuration of the plants. Configuration 5 is highlighted, representing the reference configuration, composed by symmetrical chillers.

3.3. Phase III. Energy analysis of chiller plants by solving an OCL and OSC control problem

For the selection of the optimal alternative by solving the OCL and OCS problem, the same ambient temperature values used in the thermal simulation of the demand profiles shown in Fig. 4 are assumed. It is defined as a

Table 1. Configuration of the plants.

Chiller plant	*1	* 2	Cooling capacity distribution (%)	Total cooling capacity of the chiller plant	Safety factor (%)
1	180,1	357,8	33/67	537,92	10,2
2	198,7	357,8	35/65	556,59	14,1
3	201,6	357,8	36/64	559,82	14,7
4	228,9	310,6	42/58	539,53	10,6
5	271,2	271,2	50/50	542,46	11,7
6	271,2	310,6	47/53	581,85	19,2

principle, not only to reach the optimum point of each individual chiller, but the plant to reach its optimum load. The methodology showed in Fig. 2 was applied. The OF expressed in Eq. (11) is evaluated, considering the restrictions set forth in Eqs. (12)–(15). A GA was adjusted using control parameters: population size:150; selection operator: uniform stochastic; reproduction: elitism 2; crossover factor: 0,8; mutation uniform: 0,01; crossover heuristic: 1,5

Finally, the GA progressively obtains better solutions and stops the search when the maximum number of generations is reached; or when the value of the adaptation function converges to an asymptote. The implementation of phase III of the procedure allows to identify the optimal PLR_i of each chiller at each demand point, through the established optimal sequence, the status of on and off and the number of machines in operation. This analysis was performed for all the combinations, the on-off status and PLR values were obtained. The baseline schedule of OCS strategy and the OCL solution allow that on chiller plant 1–4, the chiller with largest cooling capacity works better than the first chiller. The PLR–COP curves obtain by all chiller in the optimization process are shown in Fig. 5.

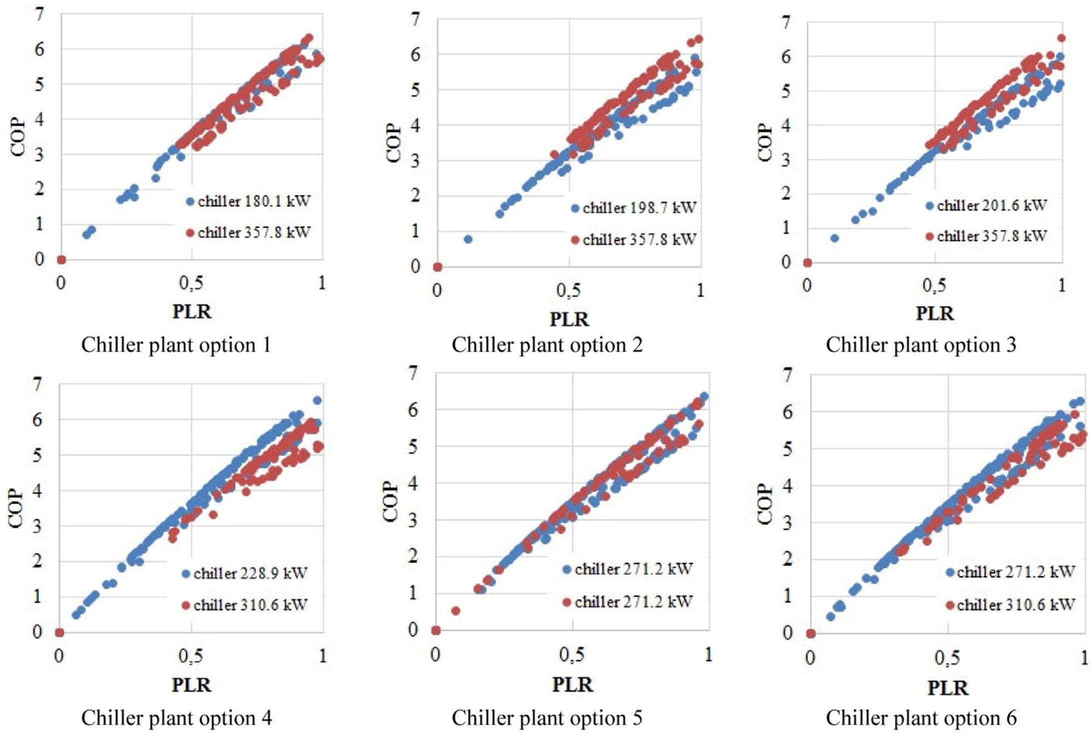


Fig. 5. COP-PLR Curves of chiller plant options.

4. Analysis of results

The chiller plant presented in option 5 and 6 (reference case) do not follow the similar strategy because of its configuration, that bring on that symmetric or almost symmetric plant has worst energy performance than asymmetric configuration and cannot adapt to all building load regime. Table 2 shows the energy consumption and COP values of all chiller plant options. The result revealed that the best configuration was option 1. Compared with the reference case, it diminishes the energy consumption about 14,4% and increment their mean COP at 12,83%.

Table 2. Energy consumption and COP values of chiller plant options.

Chiller plant	Energy consumption (kWh)	COP
1	10446,25	4,44
2	10681,53	4,31
3	10696,96	4,30
4	10596,20	4,48
5	11953,83	3,87
6	11707,87	3,99

For the LCC analysis the following considerations were considered: the Cost of Electrical Energy Consumption of each chiller plant in various (k_i) ($E_{cost,i}$) by the chiller plant was established considering the local electricity rate, which includes the different periods of the day. To determine the Initial Cost (IC), different values of reference chillers (IC_0) belonging to the Shenzhen et al. [42] were taken and the mean of the result was calculated. The depreciation value of the equipment in the last year was considered 20% of the initial investment. The discount rate for investment in the tourism sector is 12% according to Cardoso et al. [43]. To carry out the analysis of the indirect pollution, it was considered that the energy savings of each chiller regarding the reference plant. The emissions index factor for local electricity generation subject to a specific fuel (F_ε) calculated for local electric generation was taken from Meneses et al. [44], which is related as the Specific Consumption Index (C_I) of the thermoelectric plant in the territory. Applying Eqs. (19)–(26), a (PVF) equal to 7, 8431 is obtained. Table 3 shows the LCC and the indirect impact of the thermoelectric power plant.

Table 3. LCC and indirect pollution of chiller plants.

Chiller plant	Investment cost ($)	Annual cost		LCC ($)	Savings ton CO_2/year
		Operation	Maintenance		
1	107434,39	85628,95	2655,19	798595,39	63,35
2	109301,98	87375,33	2747,35	814860,98	53,46
3	109613,72	87445,89	2763,27	815846,72	52,81
4	108749,37	86385,6	2663,13	805891,37	57,05
5	109289,77	97337,39	2342,89	889810,77	0
6	112335,2	95298,99	2872,03	880982,32	10,34

The asymmetric chiller plants 1 (33/67) achieved a reduction in LCC to 11% and an emission pollution savings of 15% compared to the reference chiller plant. It is suggested to extend the design possibilities by increasing the total of chiller in a chiller plant up to 5 screw chillers. The energy analysis corresponds to the presented in the methodology proposed. The results its show in Fig. 6.

It is appreciated that a set of chiller plant with 3 and 4 chillers obtain a better energy performance of the air conditioning systems in the hotel facility. Table 4 shows the configurations that reaches the minimum LCC. This chiller plant reduces up to 24% of the LCC respect to the reference case.

Table 4. Suggested chiller plant options.

Number of chillers	Cooling capacity (kW)				SF (%)	Distribution of cooling capacity (%)	Energy consumption (MWh/year)	LCC ($)
	1	2	3	4				
4	119	119	134	180	12,9	22/22/24/33	387,7	718525,96
3	134	180	229		11,1	25/33/42	406,6	732062,55
4	119	119	119	180	9,7	22/22/22/34	392,2	736273,50
4	119	119	161	180	18,3	21/21/28/31	392,9	743904,49
3	119	199	229		11,7	22/36/42	416	744673,60

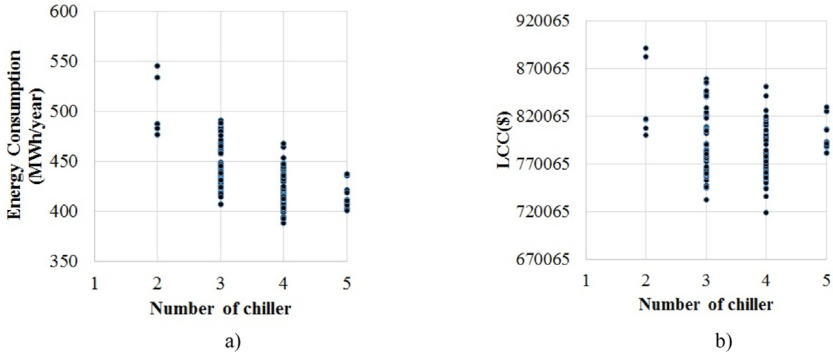


Fig. 6. Analysis of annual energy consumption and LCC for chiller plant configurations.

5. Conclusions

Chiller plants are the major energy consumption systems in a hotel facility, for that reason administrative personnel should consider preventive measures such as an efficient design to achieve future economic profits. Nowadays a typical procedure to select a chiller plant cooling capacity follows standard codes or manufacture recommendations considering. These practices do not allow to consider the energy and economics benefits in all possible combinations. The methodology to determine the optimal distribution cooling capacity of a chiller plant for a hotel facility comprises three fundamental phases:

Phase I. The statistical analysis of cooling demand profiles allows to examine the behavior of the thermal profiles through descriptive techniques and to find patterns of use that lead to establish the nominal capacity of the chillers through an iterative mathematical statistical procedure, compared to the plant design method this is a novel strategy.

Phase II. The configuration of each chiller unit in the methodology provides a mathematical procedure to establish configurations of chiller plants according to the limits established by the designer, eliminating the deterministic approach offered in the actual methodologies considered on designs.

Phase (III). The optimization process makes possible to include energy saving analysis, which is used in the robust design, the solution considers an optimization problem for OCL and OCS, using genetic algorithm.

For the solution to the OCS problem, the methodology include a strategic baseline with focus on combine sequence control methods through direct power consumption and cooling load scenarios, making it easier for the resulting chiller plant to adapted to all the hotel occupancy scenarios considering a minimal energy consumption.

The results of the case study showed that the chiller plant with lowest consumption; LCC and emission pollution with savings of 14%, 11% and 15% respectively, was the chiller plant 1 with an asymmetric configuration (33/67). By increasing the number of chillers up to 5, an improved energy performance and LCC was observed, compared to the reference chiller plant in the order of 24%.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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