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OPTIMIZATION OF A POLYGENERATION SYSTEM FOR BUILDINGS INCLUDING RENEWABLE ENERGY SOURCES

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Abstract. *Distributed power generation in buildings using renewable energies has been proposed as an important alternative for countries, in order to increase the technological base of their energy matrices. In Brazil, the possibility to incorporate this kind of distributed generation received legal support from recent electric sector regulation and energy efficiency standards, both looking for improvements in building sector. For this reason, new real estate ventures, based on environmental sustainability, are assessing the use of distributed generation in the planning stage. In this paper, we propose a superstructure composed of different cogeneration technologies to meet all residential building needs of a case study. The superstructure is optimized with programming methods based on economic objective function and technical constraints, including equipment for harnessing the available renewable energies.*

Keywords: *cogeneration, optimization methods, building, integer linear programming, district energy.*

1. INTRODUCTION

The development of urban areas has been a response to different people needs. However, the energy used in buildings for heating, cooling and lighting comprises up to 40% of the carbon emissions in development countries (Pérez-Lombard et al. (2008)). In order to reduce the environmental impact, the use of renewable energies for obtaining thermal and electrical electricity is becoming quite relevant, as it represents one solution to reduce carbon footprint. Other strategy that uses natural resources is the called *district energy system*. This alternative is efficient, reliable and environmental friendly in comparison to the traditional energy system (Alanne; Saari (2006)), where optimization and thermal system design are essential to achieve the best configuration.

A notable example is the *Polycity* project, where three large urban areas in Germany, Spain and Italy will be developed, particularly in the field of energy optimization and the use of renewable energies (Polycity, 2014). In the case of Cerdanyola (Spain), the polygeneration system will comprise a natural gas cogeneration plant with thermal cooling facilities, gasification biomass plant mainly fuelled by wood waste form the furniture industry or by subproducts from agricultural process and a solar thermal plant to produce hot water for cooling purposes. Recently, in Brazil there are recent initiatives focused on distributed generation (Sampaio et al. (2013)), where users of district system can be independent power producers, received legal support for a electric sector regulation.

In this framework, for achieving buildings and cities with higher efficient conditions, we consider the importance of developing mathematical models to take decisions about optimal configurations, considering greater number of technologies, actual costs and technological characteristics. Thus, in this work we propose to join these two mentioned strategies, applying optimization techniques in a case study found in literature. The aim is to solve it with another approach. The corresponding mathematical model is presented, in which the objective function is the minimization of the costs associated to the analysis of the superstructure equipment.

2. SUPERSTRUCTURE AND MATEMATHICAL MODEL

2.1 Case study

Here, the case study consist in a hotel complex located in Coimbra (Portugal), presented by Safaei et al. (2013). The authors work with data about energetic demand dividing the year into three seasons: Hot (H), Mild (M) and Cold (C). Hot season includes the months of June, July and August; cold season, the months of November, December and January; and finally, mild season the months of February, March, April and May. The information is given in Table 1, in the same way to was report in the paper. This includes cooling, heating and power demand with 7 block-loads: peak 1 (P1), peak 2 (P2), high 1 (H1), high 2 (H2), medium 1 (M1), medium 2 (M2) and low (L) and additional information about price grid electricity and solar systems efficiency and output.

The authors proposed three structures, where the only difference between each other was the cogeneration technology (fuel cell, microturbine and gas natural engine), whose operation includes part-load conditions. For all structures, it was included solar equipment. After the optimization process to meet all energetic demands, the authors performed an economic analysis in order to choose the best option. Now, we propose a single superstructure with several cogeneration technologies, leaving the best configuration choice to be taken by the optimization model.

Other examples can be also found in literature about optimization of cogeneration system for different kind of problems using the same tools we apply in this work. Lozano et al. (2010) built an optimization model based on mixed linear integer programming (MILP) using Lingo®. The aim was to find the best system configuration to satisfy power, cold and hot water demand for a Hospital in Zaragoza (Spain). Similarly, Bracco et al. (2013) proposed a MILP to optimize a combined heat and power distributed generation system for four buildings in Arenzano, Italy. In this case, the objective function was to minimize cost and emissions. In addition, Evins (2013) found some examples about optimized system for a sustainable building using solar technologies, using MILP. Matelli (2015) suggests using *knowledge based systems* for the conceptual design of biomass cogeneration systems, as another strategy to analyze this kind of problems.

Table 1. Case study demand data and solar systems efficiency and output.[a]

Block-load	Index	Duration	Power demand	Heat demand	Cooling demand	Grid electricity	Solar thermal efficiency	PV output	ST output
		(h/yr)	(kW)	(kW)	(kW)	(€/kWh)	%	kW	kW
Hot.peak1	H P1	276	369	0	101	0.2103	0.64	1.69	1.68
Hot.peak2	H P2	276	460	0	106	0.2103	0	0.17	0
Hot.high1	H H1	184	366	0	71	0.1136	0.35	0.8	0.37
Hot.high2	H H2	552	389	0	122	0.1136	0.63	1.02	1.55
Hot.medium1	H M1	184	293	9	25	0. 0757	0	0.14	0
Hot.medium2	H M2	368	363	0	51	0. 0757	0	0	0
Hot.low	H L	368	239	16	23	0. 0704	0	0	0
Mild.peak1	M P1	543	305	86	37	0.2103	0.59	1.72	1.44
Mild.peak2	M P2	543	378	92	52	0.2103	0	0	0
Mild.high1	M H1	362	303	120	28	0.1136	0.29	0.8	0.31
Mild.high2	M H2	1086	306	64	50	0.1136	0.52	1.17	0.9
Mild.medium1	M M1	362	230	133	1	0. 0757	0	0	0
Mild.medium2	M M2	724	287	101	45	0. 0757	0	0.1	0
Mild.low	M L	724	165	132	9	0. 0704	0	0	0
Cold.peak1	C P1	184	284	153	0	0.2103	0.42	1.31	0.69
Cold.peak2	C P2	184	329	107	0	0.2103	0	0	0
Cold.high1	C H1	644	271	97	0	0.1136	0.41	1.35	0.61
Cold.high2	C H2	184	342	123	0	0.1136	0	0	0
Cold.medium1	C M1	276	230	206	0	0. 0757	0	0.06	0
Cold.medium2	C M2	368	249	164	0	0. 0757	0	0	0
Cold.low	C L	368	153	191	0	0. 0704	0	0	0

a. Safaei et al. (2013)

2.2 Superstructure

We propose a superstructure with different kind of technologies including cogeneration and renewable resource systems schematized in Fig. 1. Cogeneration devices considered are:

- Internal combustion engine. One operating with Diesel (*Diesel Engine MCI*) and the other using natural gas (*Gas Engine ICE*). Both are power generator with water jacket to cool the engine and obtain hot water and heat exchanger to use combustion gases to obtain heating.
- Microturbine. Generates electricity and use a *HRSG* (heat recovery steam generator) to use combustion gases to obtain steam.
- Other devices are an *auxiliary boiler* that uses natural gas, *photovoltaic panel*, *solar water heating*, air conditioning using electricity (*SRC*) and absorption refrigeration system (*SRA*).

We choose satisfy a heat demand, because is easier find options to power and cooling demand (exist a possibility to use an electrical grid). With these criteria, we select existing equipments on the market to obtain technical data (fuel, steam and water mass flow, combustion gas temperature, nominal power, COP (for refrigeration systems), Heat Rate (for engines and microturbine), area (for solar collector and photovoltaic panel), cost and efficiency.

Safaei et al. (2013) included information about solar devices (photovoltaic panel power output and solar thermal output), so technical data about engines and microturbine are in fig. 2. Heat exchangers and HRSG was calculated according to primary equipment (engine or turbine) and we assume COP=3 for SRC (compression refrigeration system) and COP=0.8 for SRA.

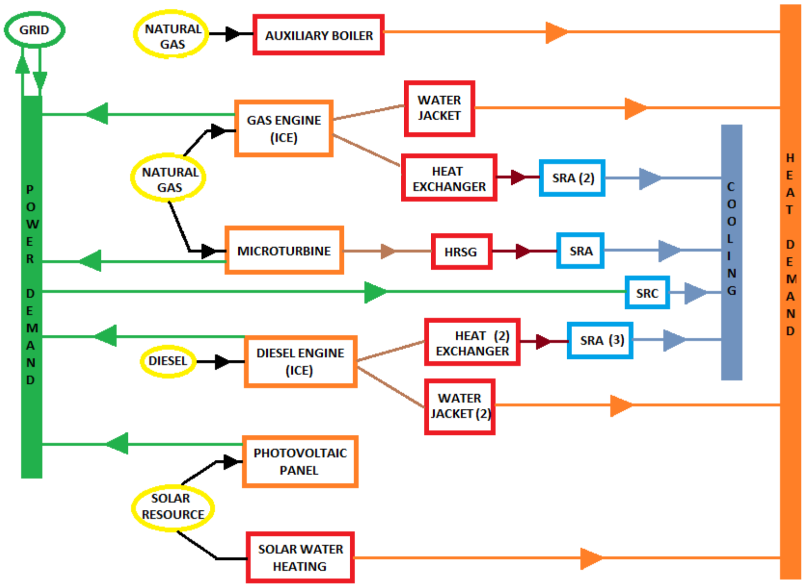

Figure 1. superstructure diagram proposed.

TURBINA CAPSTONE C600		
Output	600	kW
HR (Heat Rate)	10900	kJ/kWh
mass flow (fuel)	4	kg/s
DIESEL ENGINE CUMINS QSK23		
Output	567	kW
mass flow (fuel)	0,015	kg/s
GAS ENGINE WUAKESHA VGF/L36		
Output	460	kW
mass flow (fuel)	0,02	kg/s

Figure 2. Microturbina and engines technical data.

2.3 Mathematical Model

The model proposed has some alternatives to choose different devices. So, the software Lingo® is used to optimize the superstructure based in a MILP, including the possibility to make the structure flexible because it can buy or sell energy to the grid. As mentioned, the goal is to find the best solution in terms of economical savings (assuming investment, operation and maintenance cost for each machine and fuel cost), technical restrictions, available solar resource (in the case of solar devices) and efficiency.

We establish a mathematical model that selects the convenient configuration of the energy supply system, with an objective function, conservation of mass and energy equation (for each equipment), technical restrictions (efficiency, fuel consumption), cost information (equipment prices, operational and maintenance cost, rate of return), number of devices (just for solar equipment, because have a limit area to use) and also, we use a restriction about a quantity of cogeneration technologies to use, so the model just can choose one of this machines.

The objective function is defined to minimize fixed cost (investment, operative and maintenance) and variable cost (fuel). The investment cost is amortized for 20 years with a constant interest rate of 12%. The constraints are specified as follows. First, there are constraints for limit a number of solar devices because we have a usable limit area (530m²) to put photovoltaic and thermal solar panels. Second, there are constraints for demand satisfaction for electricity (can be supplied for gas engine, diesel engine or microturbine and photovoltaic panels), demand satisfaction for heat (water jacket and auxiliary boiler) and demand satisfaction for cooling (SRA and SRC).

2.3.1 Characteristics of the optimization model

Equation (1) shows the objetive function as a minimization of total costs (D), including total profits (R):

Min = D - R [R$/kW] (1)

Where total costs are defined as:

$D=D_{inv} + D_{comb} + D_{o\&m}+ \Sigma(EE_{purchase\_}t)$ [R$/kW] (2)

Here, invest cost (D_{inv}) is affected by the power of each equipment:

$D_{inv} = \Sigma$ (Custo_Ap*FRC*$W_{ger_}$T) [R$/kW] (3)

The other terms correspond to Fuel costs (D_{comb}), associated to Diesel and Natural gas (multiplied by each fuel mass flow), Operation and maintenance costs ($D_{O\&M}$), and the sum of purchase energy ($\Sigma(EE_{purchase\_}t)$) for each block load, being 21 block-load in total if necessary.

For other part, Profit (R) in Equation (1), it is defined as:

$R = \Sigma$ ($EE_{sell_}$T*CEC*h_T) [R$] (4)

This represents the sum of the product of the generated energy by block-load ($EE_{sell_}$T), the sales value (CEC) in R$/kW and the duration in hours of block-load (h_T). This is intended to explain profit about sell energy if structure generate more than necessary to attend consumer needs.

There are three constrains in the model. The first helps the optimization process to chose one cogeneration equipment (y1: Diesel engine, y2: Natural gas engine, y3: microturbine), from a binary variable y:

$$y_1 + y_2 + y_3 = 1 \quad (5)$$

The second constrain limits the number of solar devices to the total roof area of the hotel (530 m^2), through integer variables N1 for photovoltaic panels and N2 for thermal panels. Each one has a nominal area of 1 m^2:

$$N_1 + N_2 \leq 530 \quad (6)$$

The third constraint limits the maximum energy to be sold, regarding Portuguese legislation:

$$EE_{sell\_}T \leq 1000 \quad \text{[kW]} \quad (7)$$

2.3.2 Governing equations for equipment

Conservation equations of mass and energy refers to thermal state (temperatures, pressure and enthalpies), to obtain power and heat for each equipment with different conditions. For other hand, technical restrictions refers to device efficiency (boiler efficiency assumed in 90%, heat exchanger in 80%), limit fuel consumptions for engines, 50 to 100% for nominal mass flow and for boiler also (60 to 100% for nominal mass flow). The following equations explains as a described.

For gas turbine, fuel mass flow rate was calculated as a function of Heat Rate (HR), nominal power (W) and the Lower Heat Power (LHP) of the natural gas:

$$\dot{m}_{comb} = (HR * W)/(3600 * PCI_{gn}) \quad (8)$$

Mass flow rate of HRSG involves the efficiency (η_{cr}), mass flow rate (m_{gases}) of the exhaust gases, specific heat (CP_{gas}) of the exhaust gases, inlet and outlet temperatures ($Tgas_{in}$, $Tgas_{out}$) of the exhaust gases, water enthalpies (h_{v_tg}, h_{l_tg}) and constraint y3.

$$\dot{m}_{vapor} - (\eta_{cr} * \dot{m}_{gases} * CP_{gas} * (T_{gas_{in}} - T_{gas\_out})/(h_{v\_tg} - h_{l\_tg})) * y3 = 0 \quad (9)$$

Equation (10) defines limits to diesel mass flow for the engine, where it was included constraint y1. Equation (11) describes how to find power generate by engine for each block, in function of diesel LHP, fuel mass flow (for each block-load) and engine Heat Rate.

$$0{,}5 * \dot{m}_{nom} * y1 \leq \dot{m}_{comb\_}T \leq \dot{m}_{nom} * y1 \quad (10)$$

$$W_{mci\_}T - ((3600 * PCI_{diesel} * \dot{m}_{comb\_}T)/HR) = 0 \quad (11)$$

Mass flow rate of exhaust gases are defined in Equation (12) with a stoichiometric ratio for Diesel fuel. In Equation (13), it is found steam mass flow rate for the heat recovery system associated to the engine, as a function of the efficiency (η_{cr}), mass flow rate ($\dot{m}_{gases}\_T$) of exhaust gases, specific heat (CP_{gas}) exhaust gases, inlet and outlet temperatures ($T_{gas_{in}}$, T_{gas_out}) exhaust gases, and water enthalpies (h_{v_tg}, h_{l_tg}). Suffix "T" refers to a different block-load.

$$\dot{m}_{gas}\_T - 19 * \dot{m}_{comb}\_T = 0 \tag{12}$$

$$\dot{m}_{vapor_T} - (\eta_{cr} * \dot{m}_{gases}\_T * CP_{gas} * (T_{gas_{in}} - T_{gas\_out})/(h_{v\_tg} - h_{l\_tg})) = 0 \tag{13}$$

Equation (14) defines limits for mass flow rate of natural gas in the engine, including constraint y2. Equation (15) describes how to find power generation by engine for each block, as a function of natural gas LHP, fuel mass flow rate (for each block-load) and engine Heat Rate.

$$0{,}5 * \dot{m}_{nom} * y2 \leq \dot{m}_{comb}\_T \leq \dot{m}_{nom} * y2 \tag{14}$$

$$W_{mci}\_T - ((3600 * PCI_{gasnat} * \dot{m}_{comb}\_T)/HR) = 0 \tag{15}$$

Mass flow rate of exhaust gases are also calculated in Equation (16), with a stoichiometric ratio for natural gas. Equation (17) finds steam mass flow rate for the heat recovery system, associated to the engine, as a function of the efficiency (η_{cr}), mass flow of exhaust gases ($\dot{m}_{gases}\_T$), specific heat of exhaust gases (CP_{gas}), inlet and outlet temperatures of exhaust gases ($T_{gas_{in}}$, T_{gas_out}) and water enthalpies (h_{v_tg}, h_{l_tg}). Suffix "T" means a different block-load.

$$\dot{m}_{gas}\_T - 19 * \dot{m}_{comb}\_T = 0 \tag{16}$$

$$\dot{m}_{vapor_T} - (\eta_{cr} * \dot{m}_{gases}\_T * CP_{gas} * (T_{gas_{in}} - T_{gas\_out})/(h_{v\_tg} - h_{l\_tg})) = 0 \tag{17}$$

Equation (18) calculates steam mass flow rate for the auxiliary boiler, as a function of the efficiency (η_{boiler}), natural gas LHP (PCI_{gas}), water enthalpies (h_{out}, h_{in}) and fuel mass flow ($\dot{m}_{comb}\_T$). Suffix "T" means a different block-load.

$$\dot{m}_{vapor_T} * (h_{out} - h_{in}) - (\eta_{boiler} * \dot{m}_{comb}\_T * PCI_{gas}) = 0 \tag{18}$$

Equation (19) determines the heat released by the Absorption Refrigeration System (SRA), as a function of the steam mass flow rate generated by the Heat Recovery System of each cogenerator equipment. That is, the steam from the HRSG gas turbine ($\dot{m}_{v\_tg}\_T$), Diesel engine ($\dot{m}_{v\_diesel}\_T$) and natural gas engine ($\dot{m}_{v\_gasnat}\_T$), the coefficient of performance (COP_{sra}) and the entalphies (h_v, h_{out}). Suffix "T" means a different block-load.

$$Q_{sra}\_T - (COP_{sra} * (\dot{m}_{v\_tg}\_T + \dot{m}_{v\_diesel}\_T + \dot{m}_{v\_gasnat}\_T) * (h_v - h_{out}) = 0 \tag{19}$$

Finally, Equation (20) refers to the heat released by the Compression Refrigeration System (SRC), as a function of the Coefficient of Performance (COP_{src}) and required power ($W_{liq\_src}\_T$). Suffix "T" means a different block-load.

$$Q_{src}\_T - (COP_{src} * W_{liq\_src}\_T) = 0 \tag{20}$$

3. RESULTS AND DISCUSSION

In the work of Safaei et al. (2013), the cogenerator device was the natural gas engine. Instead, in our optimization carried out in the software Lingo®, the selected device was the Diesel motor. Besides, despite of solar technology was fixed in our initial structure, the results suggest the use of any thermal and photovoltaic solar panels. Safaei et al. (2013) only minimize costs in the objective function, while in our propose we also maximize total profits. This is because the optimized configuration can generate enough energy, even to be sold to the grid; therefore, total costs reduced. Consequently, Diesel motor operates at full-load in all block-loads.

Table 2 shows sold energy by each block-load and a variation of fuel consume for the auxiliary boiler. In our propose, heat demand and electricity generated attend costumer needs, although the priority was in the first one. In fact, heat generation is higher than costumer needs because the auxiliary boiler operates with minimum 60% of the fuel. The rest was generated by the water jacket of the Diesel engine. If the investment cost of the Diesel engine increases, or simply it is not included in the superstructure, the optimization will choose natural gas engine as the cogenerator device. This is because the investment cost of the microturbine is still higher than the gas natural engine, despite of gas natural is cheaper than Diesel.

Table 2. Results for superstructure optimization and comparison between consumer needs.

Block-load	**hours [hr/year]**	**W_{mcid} [kW]**	**Req. Power [kW]**	**Eesell [kW]**	**m_{comb} [kg/s]**	**Diesel cost [R$/year]**	**m_{comb} boiler [kg/s]**	**Heating [kW]**	**Heating demand [kW]**	**Natural gas cost [R$/year]**
HP1	276	567	369	198	0,02	50375,5	0	25	0	0
HP2	276	567	460	107	0,02	50375,5	0	25	0	0
HH1	184	567	366	201	0,02	33583,7	0	25	0	0
HH2	552	567	389	178	0,02	100751,0	0	25	0	0
HM1	184	567	293	274	0,02	33583,7	0	25	9	0
HM2	368	567	363	204	0,02	67167,4	0	25	0	0
HL	368	567	239	328	0,02	67167,4	0,00299	159,54	16	19,81
MP1	543	567	305	262	0,02	99108,4	0,00299	159,54	86	29,22
MP2	543	567	378	189	0,02	99108,4	0,00299	159,54	92	29,22
MH1	362	567	303	264	0,02	66072,2	0,00299	159,54	120	19,48
MH2	1086	567	306	261	0,02	198216,7	0,00299	159,54	64	58,45
MM1	362	567	230	337	0,02	66072,2	0,00299	159,54	133	19,48
MM2	724	567	287	280	0,02	132144,5	0,00299	159,54	101	38,97
ML	724	567	165	402	0,02	132144,5	0,00299	159,54	132	38,97
CP1	184	567	284	283	0,02	33583,7	0,00318	168,30	153	10,53
CP2	184	567	329	238	0,02	33583,7	0,00299	159,54	107	9,90
CH1	644	567	271	296	0,02	117542,9	0,00299	159,54	97	34,66
CH2	184	567	342	225	0,02	33583,7	0,00299	159,54	123	9,90
CM1	276	567	230	337	0,02	50375,5	0,00448	226,60	206	22,26
CM2	368	567	249	318	0,02	67167,4	0,00345	180,40	164	22,85
CL	368	567	153	414	0,02	67167,4	0,00411	210,10	191	27,22

4. CONCLUSION

In this work, we apply an optimization process to find an alternative solution for a cogeneration system applied to a hotel complex, previously studied by Safaei et al. (2013). The authors made an optimization of three different structures, but we propose a superstructure considering the same equipment (except the fuel cell). Results, obtained with software Lingo®, suggest a flexible superstructure, able to buy or sell electricity to the grid. Then, selling electricity, as it was found for this case, it is possible to reduce total costs (investment, fuel, maintenance and operation). In comparison with results from Safaei et al. (2013), it can be noted that our method found validation, as we obtain almost the same results despite use different methodologies. Future work will continue, based on the proposed technique, because it focus in a model that decide the best configuration from a superstructure that can attempt more technologies possibilities.

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6. RESPONSIBILITY NOTICE

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