Life Cycle Cost Analysis of HVAC systems in office buildings

The case study of EDP real estate

Nicole Landi

nicole.landi@tecnico.ulisboa.pt

Instituto Superior Técnico, Universidade de Lisboa, Portugal

July 2019

ABSTRACT

The work done in this type of thesis is comparable to a real assignment that can happen habitually to an engineer in the field of energetics in the building sector. Especially, this dissertation focused on carrying out an analysis of the costs foreseen during the whole life cycle of HVAC systems for a particular typology of construction, i.e. buildings of medium and large size used for office.

In particular, this study was commissioned by EDP Distribuçao, which intends to know the Life-cycle cost analysis of HVAC systems that could replace those already operating in ten offices located throughout Portugal.

Initially, it was indispensable to explain in detail what are the HVAC systems, describing how they are categorized, the main components and the various solutions that can be installed. After that, it was appropriate to illustrate the case studies, then all the main buildings and plant characteristics that affect the choice of the new system that can replace the existing one. Subsequently, was described the LCCA method used for the calculations, with all the assumptions adopted and the motivation behind. Therefore, a sensitivity analysis was inserted in the study, to better capture the variability of the key components that are affecting the LCCA results. The last part of the thesis was dedicated to the comments of the results obtained and to the suggestions that arose, explaining why is necessary or not to substitute the HVAC systems present in the offices.

Key-words: heating, cooling and ventilation systems in buildings; Life-cycle cost analysis; Sensitivity analysis.

1 INTRODUCTION

Energy is consistently reported as an essential resource for modern societies. The population growth and lifestyle changes have been and still are increasing the energy demand and there have been various economic (e.g., energy crisis in the 1970's), environmental (e.g., pollution from fossil fuels use) and social (e.g., armed conflicts over energy sources control/access) impacts.

The energy consumed globally in buildings makes up the largest portion, accounting for 40% of the total energy consumed worldwide. This also corresponds to 38% of the greenhouse gas emissions, reflecting the dimension of the issue both from an economic and environmental perspectives. In Portugal, the energy consumption in buildings averages 25% of the national total, but in urban areas the proportion can be up to 40% (Correia

Guendes et al., 2009). Within the various components of a building, an HVAC system is becoming an increasingly essential one. Nowadays, HVAC systems are present in any type of building, including commercial, hotels, schools, offices, hospitals or households. These systems not only account for the largest portion of the building energy consumption in most cases, but they can also occupy a large space in some cases and have a high initial investment. Therefore, is important to have the correct size and design project for the specific needs to contribute to a successful energy-efficient building. Oversizing the system is harmful to the building, in particular to the equipment durability, energy use, indoor air quality, and comfort, because the system will be short cycling in both cooling and heating modes. An HVAC system should be designed to work for a long time to reach the peak operational efficiency and avoid excess humidity present in the conditioned air distributed to the room, that can make mold inside the building.

The present thesis analyses the operational data of real office buildings to evaluate the life cycle costs (LCC) of HVAC systems, providing some basis for future studies on the viability of replacing existing systems by more energy efficient ones based using a proactive approach instead of a reactive approached based on the design life of 20 years usually adopted.

2 STATE OF ART

2.1 OVERVIEW OF AN HVAC SYSTEM

In the design phase of the construction of a new office building, it is crucial to identify the right HVAC equipment size to meet heating/cooling peak demand.

The wrong design of the HVAC system, either oversized or undersized, can have a significant impact on the CAPEX budget of the building, as HVAC cost represents on average 11% of the office building construction cost (RSMeans, 2017).

HVAC (Heating Ventilation and Air Conditioning) system is the equipment that provides heating, cooling, humidity control and it can filter outdoor air to preserve comfort conditions in a building, by controlling the air quality and the air circulation. The main goal of an HVAC system is to supply indoor thermal conditions that can satisfy the majority of the occupants.

In the design phase of a building, one of the most important phases is the choice of the type of HVAC system. In the decision process, it has to be taken into consideration plant size, the use of the building, the location (therefore climatic conditions), the typology of the building, etc.

It can be classified in two main categories: centralized system or decentralized system. Local or decentralized system is used for small or medium-sized installations. They usually handle only one space and are placed directly inside or adjacent to the room. The centralized system needs more space and/or more planes or more thermal zones from a single source. Centralized systems have different elements that can be divided into three functional categories (Grondzik, W., & Furst, R. ,2000):

- Source components, remove or provide heat or moisture
- Distribution components, connect the source with the delivery components, transporting heating or cooling medium in the building
- Delivery components, interface directly on the spaces to be heated or cooled

The HVAC systems, in addition to being able to be divided into DSSP or centralized system, can be classified according to the working fluid used within the system. In this case, it is possible to have:

- All-air system
- All-water system
- Air-water system

2.2 LIFE-CYCLE COSTING OF HVAC SYSTEMS

The technique adopted for the HVAC life-cycle cost analysis in this Thesis is presented in the Directive 2014/24/EU (SPP Regions, 2018). This method enables planners and engineers, and facilities to conduct economic analyzes and evaluate design decisions before construction or extensive design.

(B. Griffith, N. Long, P. Torcellini, R. Judkoff, 2007) develops a methodology for modelling the energy performance of commercial buildings located in various American cities with different climate. It has been shown that the structure of the building and weather affects the energy consumption. The paper reports a variation in the HVAC energy consumption from 16 kWh/m2 yr to almost 79 kWh/m2 yr according to the characteristics of the building and the site. (A. Boyano, P. Hernandez, O. Wolf, 2013) exposes a study on energy demands and potential savings in office buildings in major European cities, notably Tallinn, Madrid and London. Specifically, it follows that the energy consumption of the HVAC system in the office located in Madrid is about 30 kWh/m2 yr and Tallinn in estimated 60 kWh/m2 yr.

3 CASE STUDY AND METHODOLOGY

3.1 CASE STUDY

The office buildings studied were selected from locations covering the most relevant climatic conditions of Portugal mainland were the majority of the population is located. As such, the majority of the buildings are located in the west cost north of Lisbon (Figure 1).

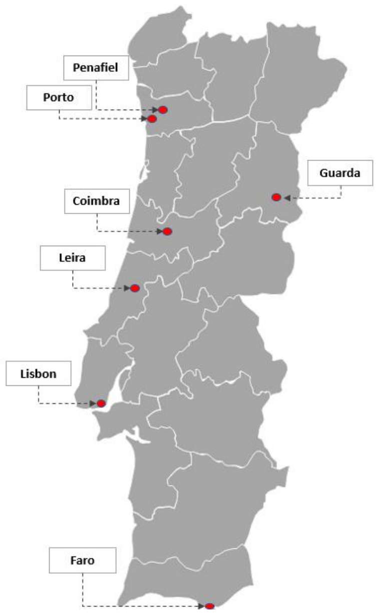

Figure 1: General overview map

This closeness to the sea and the influence of the Gulf Stream means that in the winter season, the climate is mild and temperatures below 9 °C are almost never reached during the day. It will be shown later, during the data analysis, that, with this type of climate in winter, the buildings need low power heating systems. On the contrary, during the warmer seasons, all the Portuguese territory is characterized by having very high temperatures, being necessary to install high power cooling systems that more energy than in winter.

3.2 METHODOLOGY

The Life-Cycle Cost Analysis (LCCA) is a method to estimate the overall cost during all the life of the project. It considers the purchase expense and operating costs. All the costs must be referred at the same time that is normally the present, for this reason, the overall future operating costs are discounted to the time of purchase and summed. The standard Life-cycle cost formula is described by the equation (3.1) (G. Rosenquist, K. Coughlin, L. Dale, J. McMahon and S. Meyers, *2004*):

$$LCC = IC_0 + \sum_{n=1}^{N} \frac{O\&M_n}{(1+r)^n} \tag{3.1}$$

Where: LCC - life-cycle cost (€)

IC_0 - total installed cost at year zero (€)

O&Mn - operating and maintenance cost at year n (€)

r - discount rate (%)

n - year for which operating cost is being determined

During the lifetime of any type of project, the costs can be stored in two main categories: initial expenses and future expenses. In the case of an HVAC system, the initial expenses or CAPEX are defined by the sum of two main costs: equipment and installation. The future expenses are obtained by the sum of the energy, ordinary and extraordinary maintenance costs. A useful life of 20 years is hypothesized for an HVAC system.

3.2.1 ASSUMPTIONS FOR THE MODEL

In this thesis, buildings used for real offices, which are located in various parts of Portugal, are studied.

Given that all offices were built after 2000, the main study of this thesis is to run an LCCA on the replacement of the existing plants with a new generation of the same type.

Two of the offices studied in this thesis (Leiria and Lisbon Building A) have an HVAC system installed in 2016, and thus, given their short operation life, they are considered new and high efficient; therefore, it is not necessary or recommended to replace them. So, they will not be included in the analysis.

Starting to examine each variable from the current year, which by convention of the methodology is the Year Zero, the first costs to be addressed are:

- Equipment purchase: it is assumed that it is all concentrated in the Year Zero
- Installation cost: varies according to the size of the system and it is possible to decide and fix it with the installation company. After collecting several estimates, it is possible to assume with a reasonable margin of error that the cost of installation is about 70% of the equipment purchase

The Table 1 shows the equipment purchase and installation costs on the basis of the various models that will replace the existing ones.

Table 1: Equipment purchase and installation cost of the new HVAC systems

Office	New Model	Quantity	Total equipment purchase (€)	Total installation costs (€)
Penafiel	Toshiba MMY-MAP0806FT8P-E	2	8,458.46	5,920.92
	Toshiba MMY-AP3016HT8P-E	1	11,954.25	8,367.98
Porto Building A	Daikin EWAD190TZ -PL B1	2	96,434.00	67,503.8
	Daikin EWYD320-BZSS	1	91,856.00	64,299.2
Porto Building B	Daikin EWAD220TZ -PL B1	2	109,270.00	76,489.00
	Daikin EWYD320-BZSL	1	96,445.00	67,511.50
Guarda	Toshiba MMY-MAP0806FT8P-E	1	4,229.23	2,960.46
	Toshiba MMY-MAP1006FT8P-E	1	4,745.13	3,321.59
Coimbra	Daikin EWYQ-G-XS120	1	32,743.00	22,920.10
Lisbon Building B	Climaveneta NECS-W/B 1104	1	35,167.15	24,617.01
	Climavaneta NECS-Q/B0904	1	38,510.00	26,957.00
Lisbon Building C	Daikin EWYQ-G-XS160	2	77,376.00	54,163.20
	Daikin EWYQ-F-XR 180	1	53,415.00	37,390.50
Faro	Daikin EWYQ-G-XS120	1	32,743.00	22,920.10
	Daikin EWYQ-G-XS085	1	25,702.00	17,991.40

After purchasing and installing the HVAC systems, operation and maintenance costs are incurred. These will be analysed and reported annually to facilitate calculations, by convention.

The operation costs in the specific case of HVAC systems can also be called energy costs. The latter were calculated based on the average annual consumption of past years extrapolated from energy certificates and updated according to the efficiency of the new plant to be installed. The result obtained are shown in the Table 2.

Table 2: Total annual energy consumption

Building	Total old annual energy consumption (kWh/m^{2}year) (est.)	Total new annual energy consumption (kWh/m^{2}year) (est.)	Difference (%)
Penafiel	24.66	24.25	- 1.68
Porto Building A	37.05	36.92	- 0.35
Porto Building B	88.17	82.68	- 6.23
Guarda	18.41	17.60	- 4.44
Coimbra	30.55	28.18	- 7.76
Lisbon Building B	17.04	15.71	- 7.81
Lisbon Building C	39.98	27.15	- 32.08
Faro	11.83	10.86	- 8.18

To be able to have the optimal performance of the system, it is necessary to schedule pre-established checks and maintenance interventions. In the offices studied in this thesis, it was possible to receive a list of all the ordinary maintenance carried out of the installations. It can be assumed that on average this is 5% of the equipment purchase per year for each HVAC system.

Although periodic maintenance is programmed, it is possible that parts of the system undergo damage or breakage. Even if it is not possible to foresee such extraordinary events, one can hypothesize for the calculation of the incurred cost, an indicative 3% of the purchase price, which can be assumed to be sustained every 5 years.

The discount rate value is 1.13% (10-Y Portuguese government bond yield as of April 26, 2019) and is equivalent to the value of the 10-year Portugal bond.

Finally, at the end of the 20 years, the various HVAC systems may have a salvage value (computed using the sum-of-the-digits depreciation method).

3.2.2 Sensitivity analysis

Given that, for the calculation of the LCCA, assumptions are used, thus they have a degree of uncertainty, it is advisable to include a sensitivity analysis (SA) on specific highly variable parameters.

Sensitivity analysis is a procedure to study quantitatively and qualitatively how the variation of an uncertain parameter affects the final outcome of LCCA. In fact, with this method, it is possible to slightly manipulate some inputs to see what impact they have on the result.

With regard to the HVAC system and the model adopted in this thesis it is possible to affirm that:

- The energy cost is instead an uncertain parameter because it is not possible to predict, with a reasonable degree of certainty, the energy consumption year by year. It highly depends on the climatic conditions, that differ year over year, and being a recurring cost that affects a lot on the output, it is useful to run a SA
- The discount rate is another variable with high degree of uncertainty, because it varies according to the trends of the financial markets and the economy, thus it is advised to run a SA

4 RESULTS

In the Table 3 the results of the LCCA are presented:

Table 3: Life-cycle cost analysis results

Building	LCCA (€)	LCCA (€/m^2)
Penafiel	155,515	97.79
Porto Building A	1,669,978	137.73
Porto Building B	2,615,457	207.95
Guarda	73,573	68.19
Coimbra	572,944	85.77
Lisbon Building B	612,554	58.06
Lisbon Building C	788,202	134.42
Faro	260,458	74.00

Then, it is analysed the possible savings if it is decided to replace the HVAC system. For this calculation, only the operation cost is included because it is assumed that the ordinary and extraordinary maintenance will be the same for the installed and new models. The Energy cost saving was calculated from the start year of the new plant until the end of life of the HVAC systems installed in the offices to be analysed. The result derives from the comparison of the annual operation cost of HVAC systems already installed with the new ones proposed in this thesis (Table 4).

Table 4: Energy cost saving of the new HVAC systems

Building	Old system est. installation year	Old system Est. useful life in years	New equipment purchase (€)	Total energy cost saving (€)	Average yearly energy saving (%)
Penafiel	2011	11	20,413	1,027	1.68
Porto Building A	2011	11	188,290	2,438	0.35
Porto Building B	2011	11	205,715	82,635	6.00
Guarda	2011	11	8,974	1,377	4.44
Coimbra	2008	8	32,743	17,797	7.76
Lisbon Building B	2004	4	73,677	44,506	32.09
Lisbon Building C	2008	8	130,791	15,772	7.81
Faro	2011	11	58,445	5,314	8.18

The SA was performed for the energy consumption increment and the discount rate for all buildings covered by the thesis.

In the Table 5, is shown the SA for the Penfiel's office based on simultaneous variations of-0.9%, 0.1%, 1.1%, 2.1%, and 3.1% for the energy consumption increment and 0.5%, 0.9%, 1.1%, 2.2%, and 2.7% for the discount rate. The behaviour of the results of all the other buildings is similar.

Table 5: Penafiel's LCCA sensitivity analysis

		Energy consumption increment				
		-0.9%	0.1%	1.1%	2.1%	3.1%
Discount rate	0.5%	145,127.25	154,010.99	164,048.79	175,399.26	188,242.78
	0.9%	140,654.43	149,054.84	158,538.80	169,254.63	181,370.89
	1.1%	138,196.41	146,332.94	155,514.65	165,884.27	177,603.98
	2.2%	127,756.02	134,786.46	142,702.49	151,623.64	161,685.63
	2.7%	123,385.68	129,960.86	137,356.55	145,682.89	155,064.88

5 CONCLUSION

The thesis aims to estimate economically the complete or partial replacement of heating and air-conditioning systems, maintaining the existing distribution and delivery components, in buildings used for offices, using the Life-Cycle Cost Analysis.

To compare effectively the results obtained with LCCA, the cost per m^2 was calculated as shown in Table 3. Is therefore possible to note that the highest cost occurs in Porto Building B (216% higher than offices' median), caused mainly by the highest annual energy consumption per square meter, as shown in Table 2. Thus, is therefore possible to assumed that there are some energy usage inefficiencies from the occupants, maybe due to the position of the building. The before mentioned reasoning is based on the comparison with the neighbourhood Porto Building A, that has the same building architectural style with 26% more surface and 49% less cost per square meter. Even though, Lisbon Building B with the second highest surface presents the lowest estimated cost per square meter (- 41% higher than offices' median), mainly due to the fact that has one of the lowest energy consumptions per square meter.

(A. Boyano, P. Hernandez, O. Wolf, 2013) reports the energy consumption of the HVAC system in the office located in Madrid. Knowing that the variation on the climate temperature in Madrid are ranging from an average minimum of 6°C in winter to an average maximum of 27°C in summer (WMO, 2019). This can be comparable with the climate situation in the cities of Coimbra, Porto, Penafiel, and Guarda. Looking the annual energy results obtained in the Figure 23 and the results reported in the paper, is possible to say that the conclusions are similar. On the contrary, Tallinn's climate is completely different to the Portuguese one, ranging from an average minimum of -5°C in winter to an average maximum of 18°C in summer (WMO, 2019). Thus, is understandable that the value reported in the paper is higher as it requires more energy to reach the comfort temperature for the occupants during year due to the rigid climate.

By running the sensitivity analysis with a predeterminate scenario, it is possible to note that the highest cost occurs when the discount rate is 0.5% and the energy consumption increment is 3.1%, while the lowest happens with 2.7% and -0.9% respectively. This is because, by increasing the annual energy consumption, the result of LCCA increases accordingly, while decreasing the discount rate results in a higher final cost, since hypothetically, to get the future value at n=20, is needed to invest more capital today as it will growth at lower interest rate compared to the standard scenario. Applying the same principle by decreasing the consumption of energy and increasing the discount rate, the end result will be lower.

Considering the results obtained, from the Table 4, it is possible to advise to replace the HVAC systems in the offices of Coimbra and Lisbon Building B for the following reasons:

- Comparing the model installed with the new one, there is a significant difference in the efficiency and it can be deduced that there has been a generational leap between the two models;
- For Coimbra, the estimated total energy cost saving is €17.797 in 8 years with an average yearly saving of 7.76%. The total saved value is equal to 54% of the new equipment purchase, with a payback period

of about 15 years. Similarly, for the office Lisbon Building B, in just 4 years, the estimated energy cost saving is €44.504, with an average yearly saving of 32.09%, which in total corresponds to 60% of the equipment purchase, with a payback period of about 8 years.

Regarding the Porto Building B office, it is not convenient to change all the facilities but only the two Daikin EWAD210E-SL002, being that the new model has much better efficiency. In addition, after 11 years, the total estimated energy cost saving is €74.323, which is equivalent to 68% of the equipment cost, with a payback period of 17 years.

For all the other buildings studied in this thesis, excluding Lisbon Building C, which has plants of 2008, all systems are relatively recent and have still more than half of the projected useful life. It can be inferred that, in the previous project, the choice of the plants adopted was an optimal solution for the technology at the time, with high energy efficiency. Moreover, in recent years the manufacturers have not produced competitive models that can justify replacement cost for these offices, thus is not convenient to replace the HAC systems present in these offices.

BIBLIOGRAFY

Zhu, Y., Tao, Y., & Rayegan, R. (2012). *A comparison of deterministic and probabilistic life cycle cost analyses of ground source heat pump (GSHP) applications in hot and humid climate. Energy & Buildings, 55, 312–321*.

Engeteles *(2018)*. *Plano de Manutenção Preventiva: Como Elaborar*

State of Alaska – Department of Education & Early Development *(2018). Life Cycle Cost Analysis Handbook*

S. Fuller (2006). *Life-Cycle Cost Analysis (LCCA)*

G. Rosenquist, K. Coughlin, L. Dale, J. McMahon and S. Meyers *(2004). Life-cycle Cost and Payback Period Analysis for Commercial Unitary Air Conditioners*

Walter T. Grendzik. Editor *Air-conditioning system design manual. Second edition*

SPP Regions, 2018. *State of the art report. Life Cycle Costing*

P. Torcellini, S. Pless, M. Deru, B. Griffith, N. Long, R. Judkoff, *Lessons Learned from Case Studies of Six High-Performance Buildings, Technical Report NREL/TP-550– 37542, June 2006*

B. Griffith, N. Long, P. Torcellini, R. Judkoff*, Assessment of the Technical Potential for Achieving Net Zero-Energy Buildings in the Commercial Sector; Technical Report NREL/TP-550–41957, December 2007*

L. Lecamwasam, J. Wilson, D. Chokolich*, Guide to Best Practice Maintenance and Operation of HVAC Systems for Energy Efficiency (January 2012), Pages 36–37*

A. Boyano, P. Hernandez, O. Wolf, 2013 *Energy demands and potential savings in European office buildings: Case studies based on EnergyPlus simulations*