Proceedings of the REHVA Annual Meeting Conference
Low Carbon Technologies in HVAC
23 April 2018, Brussels, Belgium

ECONOMIC OPTIMAL HVAC DESIGN FOR BUILDINGS AND CO$_2$ EMISSIONS ANALYSIS

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Abstract

In the early design phase of a building, the task of the Heating, Ventilation and Air Conditioning (HVAC) engineer is to propose an appropriate HVAC system for a given building. This system should provide thermal comfort to the building occupants at all times, meet the building owner's specific requirements, and have minimal investment, running, maintenance and replacement costs (i.e., total cost) and energy use or CO$_2$ emissions. Calculating these different aspects is highly time-consuming and the HVAC engineer will therefore only be able to compare a (very) limited number of alternatives leading to suboptimal designs. This study presents therefore a Python tool that automates the generation of all possible scenarios for given thermal power profiles and energy load and a given database of HVAC components. The tool sizes each scenario properly, computes its present total cost (PC) and the total CO$_2$ emissions associated with the building energy use. Finally, the different scenarios can be searched and classified to pick the most appropriate scenario. The tool uses static calculations based on standards, manufacturer data and basic assumptions similar to those made by engineers in the early design phase. It should further be noted that the tool optimizes the HVAC system but not the building envelope, while, ideally, both should be simultaneously optimized.

Keywords: optimal design; HVAC; CO$_2$ emissions; building; GEOTABS; ground source heat pump

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1. Introduction and Existing Design Methods

In Europe, buildings are responsible for 40% of the total energy use from which half is used for heating and cooling [1]. In accordance to the European Union's Directive 2010/31/EN [2], the energy requirements for buildings are becoming increasingly stringent. Not only should the buildings become more energetically efficient through a better design of the building envelope (insulation, shading, etc.) and the use of more efficient HVAC devices, but buildings are also obliged to use renewable energy sources. Both requirements put building designers and installers under pressure to be innovative and up-to-date with the various and rapidly improving available technologies. Furthermore, systems are becoming increasingly complex. Whereas a standard gas- or oil-fired boiler and a compression cooling machine connected to radiators and ventilation units used to be installed everywhere, buildings using a combination of production systems such as gas boilers, heat pumps, etc., emission systems such as radiators, fan coil units, chilled beams, TABS, etc., and additional renewable energy sources such as photovoltaic panels, solar boilers, borefields, etc. are becoming common in Europe. With this increase in system complexity and the lack of knowledge about these new and rapidly improving technologies, design tools are becoming highly necessary to help designers and installers to optimize both the design and the control of buildings. According to Ellis and Mathews [3], researchers believe that design tools based on an integrated approach where the system efficiency is optimized taking the interactions between the various components and their constraints into account could lead to savings around 70%. However, such design tools are confronted to an intricate problem. Firstly, the number of design variables (type, size and combination of systems) is usually very high. Secondly, the operation efficiency of each system is very dependent on its components and how they interact, and, finally, the design is heavily based on the building's energy demand, which is difficult to predict in the early design phase.

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In the literature, building and HVAC designs are typically optimized by heuristic methods such as genetic algorithms [4, 5, 6, 7]. Due to their slow convergence, generally only a limited number of parameters are optimized while the control is fixed or optimized over a short period of time. Another popular approach is to formulate the optimal design problem as a *mixed integer linear programming* (MILP) problem, allowing many variables to be solved in a reasonable computing time [8, 9, 7]. However, a MILP formulation requires linear models that hampers its use in simulation based building design optimization.

On the more practical and political sides, EU's Directive 2010/31/EN compels the EU countries to limit the energy used by the building sector but leaves each country the freedom to develop its own legislative framework to reach the energy goals. In Belgium, a software called EPB (in Dutch and PEB in French) is used to compute an energy level indicator. The energy level is evaluated based on quasi static energy loss computations and on a point table to grade different HVAC systems. The Flemisch Energy Agency (VEA) publishes every second year a report that investigates for which energy level the building would also be cost optimal with respect to the sum of investment, running and replacement costs [10]. While the results are very instructive for decision makers of Flanders, the method is not practical for designers as it is difficult to relate the energy indicator to real energy use and the initial assumptions and approximations made by the static calculation method of the EPB software are very steering. Furthermore, the EPB software is not able to calculate dynamic aspects, system integration and control correctly.

The drawback of the presented methods is that they require intensive computer power, specialized software, and intensive modelling and set up work. Furthermore, the results are difficult to analyse as they are influenced by numerous optimization parameters and assumptions/approximations made by the tools. Therefore, this work proposes to go back to the straightforward, but time-consuming method used by engineering offices and to automate it. The method should be based on a limited set of parameters, and it should remain intuitive to be usable in the early design phase. The starting point of the method consists of the heating and the cooling *load duration curves* (LDC) of the building, which represent the thermal powers required to condition the building. These thermal powers are ordered and each power is plotted with a width equal to the sum of hours that it is used, such that the integral of the LDC represents the yearly energy load of the building. The developed method proposes then all possible HVAC scenarios composed of the devices present in the database, which can provide the powers and the energy load of the LDC and computes the scenarios PC (including the investment, running, maintenance and replacement costs) and CO_2 emissions (see section 2). The method has the main advantage to automatically generate and size, and to return the necessary information about each possible HVAC scenario such that design engineers can make the optimal choice, while the method complexity is sufficiently low such that the results can be easily manually verified.

This paper is structured as follows. Section 2 introduces the methodology proposed in this work, and section 3 lists the considered HVAC components and summarizes their characteristics. Finally, section 4 illustrates the use of the tool on a case study and section 5 summarizes the conclusions.

2. Methodology

The methodology used by the developed tool to optimize the HVAC system for a given building is schematically represented in fig. 1, which shows the four steps that are consecutively carried out. This section provides a concise summary and interested readers are referred to Picard and Helsen 2018 [11] for more details about the methodology and assumptions.

Step 1 consists of creating a database of HVAC components containing for each component (see section 3): its cost function returning its price as a function of its size (kW, m^2, etc.), its maintenance cost, its life expectancy (see table 1), and its energy efficiency for different temperatures if it is a production component or its nominal supply and return temperature for emission devices. Additionally, a number of building parameters are required such as its total floor area (used to size the Concrete Core Activation (CCA) system) and the ground characteristics that influence the borefield design.

Step 2 generates all possible HVAC scenarios composed of the devices present in the database, which can deliver the energy and thermal powers of the given LDC using the HVAC components of the database. Firstly, a set of production and emission systems is taken from the available components of the database. The components can be monovalent or bivalent (heating/cooling). Secondly, the production systems are sorted by decreasing efficiency and the heat (cold) emission system with the lowest (highest) supply temperature is coupled to the

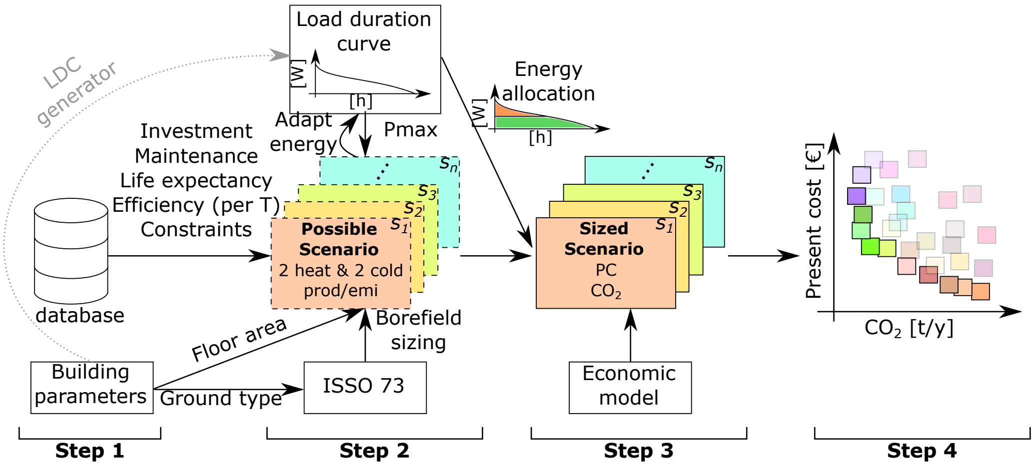

Figure 1: Schematic representation of the optimal Heating, Ventilation and Air-Conditioning (HVAC) design methodology split in four consecutive steps. The generation of load duration curves (LDC) based on a limited set of building parameters is not yet implemented and is therefore represented as a dotted grey arrow.

most efficient heat (cold) production system. The maximum heating (cooling) power *present* in the LDC can now be divided between the different heat (cold) systems according to predefined hybrid fractions. This means that for a predefined set of components (e.g. a heat pump + tabs + gas boiler + compression cooling machine + fan coil units) different scenarios are generated. For example, for scenario 1, the base load system will cover 25% of the power while the back-up will cover the remaining 75%, scenario 2 will use a 50-50% distribution, etc. (see [11] for more details). While most of the components are sized according to their nominal power, CCA and Floor Heating (FH) are sized to a realistic fixed 80% of the building floor surface area and the ground heat exchanger (i.e., the borefield) is automatically designed according to standard ISSO 73 [12]. It should be noted that the tool does not generate LDC's but it is an input to the tool.

Once the type and the size of each HVAC component of a scenario are defined, the energy from the LDC can be allocated to the different production components such that the most efficient component delivers the base load (**Step 3**). Notice that fig. 1 shows only one LDC while actually two LDCs are needed: one for heating and one for cooling. The scenario present cost (PC) can now be computed as:

$$\mathrm{PC} = I_0 + \sum_{j=1}^{N} \left[\left(C_\mathrm{e} + C_\mathrm{m} + C_\mathrm{r} \right) R_j \right] - V_\mathrm{r} R_N, \tag{1}$$

with I_0 the initial investment cost calculated as the sum of the different component cost functions (see table 1), N the number of years during which the system will be used (in this work, 20 years is assumed), C_e, C_m, and C_r the yearly energy, maintenance, and replacement costs computed using the efficiencies, maintenance percentages, and life expectancies of Tables 1–2 and a given electricity and gas price of 0.1466 and 0.0534 €/kWh [13, 14], and V_r the remaining value of the system after N years (calculated linearly with the number of years the device can still be used). Besides the PC, the total CO_2 emissions caused by the energy use of the building are computed using the primary energy conversion factor of 0.056 kg/MJ for gas and 0.179 kg/MJ for electricity [10].

Finally, **step 4** compares the PC and the total CO_2 emissions of each scenario over a realistic 20 years lifetime of the building such that the design engineer can make the most appropriate choice. Note that the energy consumption calculations assumes constant efficiencies (no part load performances are taken into account).

3. Components Information

As described in section 2, the first step to optimize the HVAC system is to gather the necessary information about its components. The nomenclature, the cost function, the maintenance cost, and the life expectancy of each considered HVAC component are listed in table 1. The cost functions are derived from the (installed) cost data of 18 recently built buildings from two different Belgian engineering offices. The maintenance costs, expressed as a percentage of the investment cost, and the life expectancies are retrieved from standard NBN EN 15459 [15]. The database can easily be extended with new components provided that the required parameters are known.

Table 3 contains the assumed energy conversion efficiencies of the different heat and cold production components for different supply temperatures, based on the average of values found in technical sheets of different manufacturers and in the IEA ECBCS Annex 48 report [18]. When the efficiency is not given, it means that the component cannot supply water at that particular temperature. For the emission components, table 2 indicates their nominal conditions for heating and cooling, the ratio between their cooling and their heating power and their efficiency. The emission system effiencies are taken from NBN EN15316-2-1:2007, and they are based on the system additional heat losses. These heat losses are due to the non-uniform internal temperature distribution in the conditioned zones (caused by stratification, heat emitters along outside wall/window, differences between air temperature and mean radiant temperature), the non-ideality of the operative temperature control (causing temperature variations and drift) and the extra heat losses of heat emitters embedded in the building structure towards the outside.

4. Example

This section applies the design tool to a retirement home of 10 000 m^2. Table 4 describes the general parameters of the building and fig. 2 shows the heating and cooling curves of the building. As table 4 and fig. 2 show, the building is heating dominated but it needs a larger cooling power than heating power. The building is further very well insulated and it only needs 22 W/m^2 for cooling and 13 W/m^2 for heating. Finally, as it is usually the case in a retirement home, the number of full load hours (FLH) is high.

Table 5 gives a summary of the CO_2 emissions and the different costs of 4 different scenarios from the 549 scenarios generated by the design tool for the building described by fig. 2 and table 4.

The results indicate that if an aquifer thermal energy storage (ATES) is possible, such a system combined with TABS has the lowest CO_2 emissions (5.3 $kg/y/m^2$) and the lowest present cost (50.2 €/20y/m^2) when evaluated on the 20 years life time of the HVAC system. A conventional system composed of a condensing gas boiler (CGB), a compression cooling machine (CCM) and 4 pipes fan coil units (FC4P-HT) produces twice as much CO_2 emissions (11.2 $kg/y/m^2$) and it has a total cost of 20% higher than the ATES system (60.3 €/20y/m^2). However, if only the investment cost is considered, the conventional system is a factor 2.5 cheaper (13.1 €/m^2 instead of 32.4 €/m^2). If an ATES system is technically or legally not possible, the conventional system is the cheapest alternative but installing a hybrid system with a ground source heat pump (GSHP) to cover 25% of the heating and cooling base loads is only 10% more expensive (66.3 €/20y/m^2) and allows a saving of 20% of CO_2 emissions. Finally, if a pure geothermal system is preferred, 40% of the CO_2 emissions can be saved (6.3 $kg/y/m^2$) but the total cost is increased by 30% (79.8 €/20y/m^2).

5. Conclusions

This paper presents a tool developed in Python to automatically compute the present cost (PC) and CO_2 emissions of all possible HVAC designs of a given building with given heating and cooling loads. The computed PC includes the investment, running, maintenance, and replacement costs and the rest value at the end of the 20 years life time of the HVAC system. The method has the main advantage that it automatically generates, sizes, and returns all necessary information about each possible HVAC scenario such that design engineers can make the optimal choice to fit the client's needs and preferences. Furthermore the method complexity is sufficiently low such that the results can be easily manually verified. The tool was applied to a retirement home example to illustrate its strengths in helping the design engineer in his/her decisions.

Acknowledgement

The authors gratefully acknowledge the financial support by the IWT and WTCB in the frame of the IWT-VIS Traject SMART GEOTHERM focusing on integration of thermal energy storage and thermal inertia in geothermal concepts for smart heating and cooling of (medium) large buildings. The authors also acknowledge the funding of their research work by the EU within the H2020-EE-2016-RIA-IA programme for the project

Table 1: Abbreviation (Abb.,) name, cost function with its lower and upper bounds (∞ means that extrapolation is allowed), Maintenance (Maint.) cost in percentage per year of the investment cost and Life Expectancy (Exp.) of each Heating, Ventilation and Air-Conditioning (HVAC) component, currently included in the database.

Abb.	**Component**	**Cost Function [€] (*1)**	**Maint. Cost [%/y]**	**Life Exp. [y]**
CGB	Condensing gas boiler	$85.405x + 9451$(*6) $x \in [25,\ 800]$ kW	1.5%	20
GSHP / WSHP	Ground or Water source heat pump	$83.368x + 11725$ (*6) $x \in [34,\ 300]$ kW	3.0 %	20
CCM	Compression cooling machine	$80.084x + 12456$(*7) $x \in [21,\ 1335]$ kW	4.0%	15
GSPC / WSPC	Plate HEX for passive ground or water source cooling	$14.421x + 1814$(*7) $x \in [28,\ 472]$ kW	2% (*2)	20 (*2)
GHEX-V	Vertical ground heat exchanger	$32.0x$ (*3) $x \in [0,\ \infty]$ m	0.25%	50
ATES	Aquifer thermal energy storage	$10417.061x^{0.438}$(*4;6) $x \in [38,\ 1050]$ kW	2% (*5)	40 (*5)
R-HT	High temperature radiator	$134.100x$(*6) $x \in [0, \infty]$ kW	1.5%	35
R-LT	Low temperature radiator	$287.791x$(*6) $x \in [0, \infty]$ kW	1.5%	35
FC2P-HT-coo	High temperature 2-pipes fan coil unit (cooling)	$456.621x$(*7) $x \in [0, \infty]$ kW	4.0%	15
FC2P-LT-coo	Low temperature 2-pipes fan coil unit (cooling)	$267.142x$ (*7) $x \in [0, \infty]$ kW	4.0%	15
FC4P-HT	High temperature 4-pipes fan coil unit (reversible)	$223.814x$ (*6) $x \in [0, \infty]$ kW	4.0%	15
FC4P-LT	Low temperature 4-pipes fan coil unit (reversible)	$397.417x$ (*6) $x \in [0, \infty]$ kW	4.0%	15
CCA	Concrete core activation	$21.650x$ $x \in [0, \infty]$ m^2	2.0 %	50
FH	Floor heating	$34.593x$ $x \in [0, \infty]$ m^2	2.0 %	50
CC	Cooling ceiling	$2500x$ (*6) $x \in [0, \infty]$ kW	2.0 %	30

(*1) Based on cost data from real buildings. (*2) Assumption based on VEA2013 [10] because no data in NBN EN 15459 [15]. (*3) Data provided by Boringen Verheyden [16]. (*4) Cooling power is assumed to be 78% of heating power based on (*5). (*5) Data provided by IFTECH [17]. (*6) Based on heating power. (*7) Based on cooling power.

Table 2: Parameters of emission components (component abbreviations are explained in table 1). Nominal conditions are given as $T_s/T_r/T_a$ with T_s, T_r and T_a the supply, return and zone air temperatures. The power ratio column indicates the ratio between cooling and heating powers for reversible systems and the last column introduces a correction factor ($\eta_{\textbf{HVAC}}$) for the energy use of the emission system to represent the suboptimality of its control.

	Nominal Conditions (°C)		**Power Ratio**	$\eta_{\textbf{HVAC}}$
	Heating	**Cooling**	**Cooling/Heating**	**(*4)**
CCA // FH // CC	30/-/- // 35/-/- // 30/-/-	20/-/-	125%$^{(*1)}$ // 30%$^{(*2)}$ // 250%$^{(*3)}$	0.83
HTR // LTR	60/50/20 // 45/35/20	-	-	0.91
FC4P-HT // -LT	60/50/20 // 45/35/20	10/15/25 // 15/20/25	60% // 63%	1
FC2P-coo-HT // -LT	-	15/20/25 // 10/15/25	-	1

(*1) It is assumed that CCA can provide a maximum of 40 W/m^2 for heating and 50 W/m^2 for cooling;
(*2) It is assumed that FH can provide a maximum of 100 W/m^2 for heating and 30 W/m^2 for cooling;
(*3) it is assumed that CC can provide a maximum of 40 W/m^{2}for heating and 100 W/m^{2}for cooling;
(*4) Taken from NBN EN15316-2-1:2007 [19].

Table 3: Efficiencies of production components based on values from technical datasheets (TS) and Annex 48 [18]. In the case of GSHP, the given efficiency corresponds to the Seasonal Performance Factor (SPF) assuming a circulation pump power of 2.5% of the heat pump thermal power. The Coefficient of Performance (COP) is given in brackets and it is evaluated for a source temperature of 5 °C for GSHP and 10 °C for WSHP.

	Efficiencies [-]							
	30	**35**	**45**	**60**	**10**	**15**	**20**	**[°C]**
CGB	1.06	1.06	1.02	0.98	-	-	-	(*1)
GSHP	4.91 (5.60)	4.44 (5.00)	3.55 (3.90)	2.62 (2.80)	-	-	-	(*2)
WSHP	5.45 (6.3)	4.96 (5.7)	3.94 (4.4)	2.8 (3.0)	-	-	-	(*2)
GSPC	-	-	-	-	-	20.00	20.00	(*3)
WSPC	-	-	-	-	-	40.00	40.00	(*4)
CCM	-	-	-	-	3.90	4.30	4.70	(*5)

(*1) from TS: Riello [20]. (*2) from TS: AlphaInnoTec [21], Carrier [22], Viessmann [23], Daikin, Stiebel-Eltron. (*3) Common assumption. (*4) from IFTECH [17]. (*5) from Annex 48 [18].

A_{floor}	10 000 m^2
$P_{\max}$	216 kW (Cooling), 132 kW (Heating)
P_{spe}	22 W/m^2(Cooling), 13 W/m^2(Heating)
FLH	1506 h (Cooling), 3322 h (Heating)

Table 4: Building parameters: floor surface area (A_{floor}), maximum and specific heating and cooling power ($P_{\max}$, P_{spe}), and full load hours (FLH).

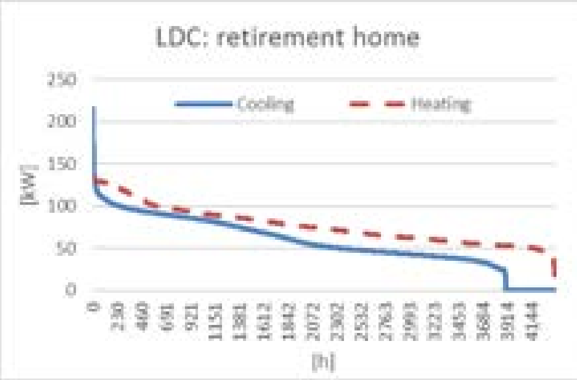

Figure 2: Heating (dashed line) and cooling (solid line) load duration curves.

Table 5: Summary of the emissions and the different costs of 4 different scenarios from the 549 scenarios generated by the design tool for the building described by fig. 2 and table 4. The first column indicates the scenario number in the list ordered by increasing total cost, the second column describes the HVAC scenario with its components and powers and the remaining columns contain the CO_2 emissions, investment (I), energy (E), maintenance (M), replacement (Repl) cost, and total cost (TOT) and the rest value (Rest).

#	HVAC system	CO_2 [kg/y/m^2]	I	E	M	Repl	Rest	TOT
					[€/20y/m^2]			
1	WSHP (132 kW), WSPC (216 kW), CCA	5.3	32.4	16.3	9.1	0.0	-7.5	50.2
32	CGB (132 kW), CCM (216 kW), FC4P-HT	11.2	13.1	38.3	6.4	5.9	-3.3	60.3
75	GSHP (34 kW), CGB (99 kW), GSPC (54 kW), CCM (162 kW), CC, R-HT, FC2P-coo-LT	8.4	34.3	28.1	7.8	3.7	-7.5	66.3
237	GSHP (132 kW), GSPC (216 kW), CCA	6.3	71.8	19.4	7.5	0.0	-18.9	79.8

‘Model Predictive Control and Innovative System Integration of GEOTABS;-) in Hybrid Low Grade Thermal Energy Systems - Hybrid MPC GEOTABS’ (grant number 723649 - MPC-; GT). The authors would further like to thank Boydens Engineering (Zedelgem, Belgium) and Ingenium N.V. (Brugge, Belgium) for sharing their cost data.

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