OPTIMIZATION METHOD FOR THE VENTILATION SYSTEM CHOICE IN ZERO ENERGY BUILDINGS

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ABSTRACT

Developing a method to optimize the investment cost of a building and the energy performance, represented by the energy consumption, one gets easily confronted with conflicting objects. As the investment cost usually rises, while the energy consumption shrinks it is somehow difficult to find an optimal solution. The utopic point would be the point where saving energy doesn't cost athing, or even better: earns the occupant extra money. Reality however shows different: restricting the energy losses almost always implies an investment. The simplest example is increasing the thermal resistance of the building envelope ((i.e. walls, roofs, floors, windows and airtightness). Since this paper handles about the ventilation system choice in zero energy buildings, it can be said that no further addition of insulation of airtightness is needed, because the heat losses through the building envelope have already been restricted to a minimum. The main issue in this paper is the control of heat losses due to the ventilation rate of the ventilation system, albeit purely hygienic or not.This paper presents a methodology for ventilation systemselection based on the total investment cost for the system and effect it has on the energy consumption of the building. Former research has shown that the choice for a cost optimal ventilation system depends on the total energy demand of the building. The proposed method makes it possible to compose a random combination of parameters (insulation thicknesses, U-values (thermal transmittance) of windows and airtightness) and calculate the heat losses through the building envelope. Through this loss of heat, the energy consumption or energy demand for the building can be calculated and an optimal choice for the ventilation system can be made, taking into account the additional cost and the system efficiency.

KEYWORDS

Optimization, ventilation system choice, zero energy building, investment cost

1 INTRODUCTION

While several studies where developed to optimize the building envelope at first and afterwards start to optimize the technical applications, this project takes a different approach. As a start, it is important to understand that every building is different. Every building has differences in geometry, orientation, material use, location (climate issues)... which means every building needs to be approached as such. Measures with respect to insulation thickness, airtightness, heating systems and ventilation units have a whole different impact depending on the architectural concept of the building. The scope of this paper is to establish a method to ease the decision making process for ventilation systems in nearly zero energy buildings.

Reviewing recent literature for European ventilation systems, it's clear that national regulations according to indoor air quality (IAQ) for buildings is a very important issue to study. Different governmental institutions in

Europe use different acceptability values for the presence of polluents in the air (Dimitroulopoulou, 2012). CO_2 is the most significant parameter in most of the cases , because it's an indication for the presence of people in a room or a building. A lot of investigations have been done on health problems and allergic reactions (asthma, rhinitis, …) of children and elderly in relation to the ventilation system installed and the amount of polluted air in rooms. Several ventilation techniques have been investigated, as for stratum ventilation (Lin ea., 2011), displacement ventilation (Lin ea., 2011, Lee and Lam, 2007), hybrid ventilation systems (Kionakis, 2005, Ji ea., 2009, Zhai ea., 2011, Kwon ea., 2013, Niachou ea., 2008), natural ventilation systems (Zhai ea., 2011, Chu ea., 2011, Niachou ea., 2008, Tan and Wong, 2012) and a whole lot of other natural and mechanical systems. The research done often focusses on the energy consumption of the systems and the impact of health considerations. These considerations imply a minimum of fresh air in a room, which means a minimum fresh air flow is required and the polluent concentration can't exceed a limit value. Moreover, the building airtightness should be taken in account for that matter. These parameters affect the energy use of a ventilation system to a significant extent (Ramponi and Blocken, 2012, Santos and Leal, 2012, Nabinger and Persily, 2011).
Authors usually allude to minimize the energy consumption by reduction of the heat losses, even apart from the building sector (Beusen ea., 2013). Increasing the airtightness of the building envelope is a strategy often used to restrict the thermal losses due to air flow. It's however important to notice that accomplishing airtightness of a construction is more effective in construction phase than as part of a retrofit operation. When making a building airtight, one should take this in account while the building is realized, not afterwards (Nabinger and Persily, 2011).
To assess the efficiency of a ventilation system, several methods are being used. A lot of research has been done using dynamic simulation software (TRNSYS) or Computational Fluid Dynamics simulation software (ANSYS). These simulation programs make iterative calculations using time steps of one hour to estimate the energy consumption of a ventilation system, based on weather data, occupancy and air humidity controlled system activation, system efficiency… The results of these investigations almost always show a reduction of the energy consumption of the ventilation system and it seems like it's always better to restrict the energy losses to a minimum. However, none of the researchers talks about the additional investment costs for a more efficient ventilation system. It's important to understand that a reduction of energy use can only be justified if the additional cost is not to high and can be paid back over a relative short period.
Some authors mention as well that occupants behavior is a very important factor to be taken into account. This parameter is very difficult to determine, because everyone behaves differently and a lot of zero-energy house owners have nor experience, nor advanced knowledge about the subject of low-energy life. It's often mentioned that ventilation systems, their settings and their functioning motives require some instructions and some education. A system that is not being used in the proper way can be very inefficient and cause additional costs or discomfort and off course due to health reasons that's not an option.
Optimization of the choice for a type of ventilation depends on a lot of parameters. Some authors use genetic algorithms [Beusen ea., 2013, Hamdy ea., 2011, Magnier and Haghighat, 2010, Wang ea., 2005, Coley and Schukat, 2002, Verbeeck, 2007) in their optimization process, others rely on a mathematical method they developed (Kapsalaki ea., 2012, Dall'O ea., 2013). In this paper we intent to explain an developed mathematical method to make a decision for a typical ventilation system, based on calculations for energy consumption and total investment cost. The methodology takes into account the budget of the client and energy performance of the ventilation system.

2 METHODOLOGY

2.1 Building design and architectural concept

To get a grip on the intentions of this paper, it's important to realize the collaboration of all parts of a building. It's impossible to state that for every building insulation measures will cause a decrease of the energy consumption. In some cases overheating will occur and a cooling device will be necessary. The same statement goes for glazing and ventilation systems. Moreover the architectural concept will influence the process of decision making. It's clear that increasing the insulation thickness in a cavity wall by 5 cm is far more expensive for a detached house than for a semi-detached or even a terraced house, since there are a lot more walls in contact with the outer environment. Dwellings with a big area of glazing on the southern façade, will profit from a change of glazing type a lot faster than building with no glazing at all in the southern walls. These examples show that every building needs to be studied as a whole, not as a combination of parts or as a simplified model.

To compare the several ventilation systems, it's necessary to know what impact the ventilation systems have on the total energy consumption. All systems have a different efficiency, blow or extract a different air flow and have (or not) a heat exchanging system with a specific efficiency. It's clear that again, not 2 systems are the same. In essence, 4 general ventilation systems can be distinguished. They are collected in

Table 1: General ventilation systems.

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Ventilation system	air supply	air extraction
System A	natural	natural
System B	mechanical	natural
System C	natural	mechanical
System D	mechanical	mechanical

Since this paper focusses on zero energy buildings some important nuances need to be made. As scientist we don't intent to decide purely on gut feeling and for that matter ventilation systems A and B cannot be excluded. It's however important to recognize that ventilation system A is not very energy efficient and that ventilation system B is almost never being applied. There is off course a reason for this trend and it has a lot to do with the controllability of the systems. Using ventilation systems A and B causes the heat losses through ventilation to be uncontrollable because there is no brake on the outgoing indoor air. Better and far more responsible would it be to apply a ventilation system C or D, where the amount of outgoing hot air is more steerable. For that reason, ventilation systems A and B are (for now) being excluded.
Ventilation systems C and D can be used for nearly zero energy buildings and can even be subdivided according to their applications, their control system and their heat exchange units. All these factors are important to be taken into account while evaluating the systems and making a comparison between them. For this study some systems C and some systems D are evaluated and compared. In *Table 2: Investigated ventilation systems and their parameters for the calculation of the energy performance and the total investment cost*, the investigated ventilation systems are listed. This list is sufficient to demonstrate the methodology of decision making, but can off course be expanded for practical applications.

Table 2: Investigated ventilation systems and their parameters for the calculation of the energy performance and the total investment cost

Ventilation system	r_{heat} [-]	r_{cool} [-]	m [-]	P_{fans} [W]	IC_T [€]
0	1,00	1,00	1,50	0,00	0
C	1,00	1,00	1,50	33,30	€ 1.500
C_{he}	1,00	1,00	1,20	27,30	€ 1.000
C^+	1,00	1,00	1,08	33,30	€ 3.300
D^+	1,00	1,00	0,94	54,50	€ 4.000
D_{he}	0,27	1,00	1,40	92,30	€ 5.000

Table 2 contains indices 'he' for 'heat exchanger' and '+' for demand controlled systems. These systems can be controlled by occupancy, CO_2 concentration or relative humidity.r_{heat} and r_{cool} are correction factors for cooling and heating modus of the ventilation system and indicate a bypass of the heat exchanger in system D, while m is a correction factor for the execution quality of the system. The energy consumption for the fans is listed below P_{fans} and contains the power for all needed fans. For systems C only 1 fan is sufficient, for systems D 2 fans are required, which explains the overall difference between the power amounts.

2.2 Energy consumption calculations

To estimate the saving of energy due to the ventilation, the norms and regulations for the Belgian building industry have been consulted. These formulas are the same formulas as the ones implemented in the EPBD, the European directive on energy efficiency of buildings.

The heat losses due to ventilation and in/exfiltration of air through the building envelope can be calculated using the following formulas. These formulas result in a value in W/K and this value needs to be multiplied by the difference in temperature between the inner and the outer environment.

For the calculation of the heat losses in heating modus:

$$H_{V,heat,seci} = 0{,}34 \; . \; V_{in|exfilt,heat,seci} + r_{preh,heat,seci} \, . V_{dedic,seci} + V_{over,seci} \quad W \;\; K \qquad (1)$$

For the calculation of the heat losses in cooling modus:

$$H_{V,cool,seci} = 0{,}34 \; . \; V_{in|exfilt,cool,seci} + r_{preh,cool,seci} \; . \; V_{dedic,seci} + V_{over,seci} \quad W \;\; K \qquad (2)$$

with:

$V_{in|exfilt,heat,seci}$
$V_{in|exfilt,cool,seci}$ airflow due to leakage through the building envelope, respectively for heating calculations and for cooling calculations. How to calculate these values doesn't belong to the scope of this investigation

$V_{dedic,seci}$ designed air flow through the ventilation system, calculated using the formula beneath.

$r_{preh,heat,seci}$
$r_{preh,cool,seci}$ the value of the reduction factor for the effect of preheating of the air flow on the net energy demand, respectively for heating calculations and for cooling calculations.

$V_{over,seci}$ the extra air flow owing to over ventilation, when systems with mechanical extraction of air are connected to a heat pump for the preparation of domestic hot water, using the extracted air as a heat source. This parameter is a very interesting one, but can't be used because a consistent calculation method hasn't been developed yet. The default value for this parameter is 0 m³/h, the parameter hasn't been taken into account.

The designed air flow through the ventilation system can be calculated using following formula.

$$V_{dedic,seci} = \; 0{,}2 + 0{,}5 \; . \; exp \; -V_{EPW} \;\; 500 \;\; . f_{reduc,vent,seci} \; . \; m_{seci} \; . \; V_{seci} \;\; m^3 \;\; h \qquad (3)$$

with:

V_{EPW} the total volume of the building.

$f_{reduc,vent,seci}$ a reduction factor for ventilation. The default value for this factor is 1, but more favorable can be specified, taking into account the directives from the Flemisch Minister for Energy.

m_{seci} a multiplication factor depending on the ventilation system and the execution quality of it.

V_{seci} the total volume of the studied energy sector.

Integrating these heat losses on a yearly basis, implementing hourly temperature differences, the total energy consumption due to heat losses caused by the ventilation system can be determined. Next to these heat losses, the operation energy for fans needs to be taken into account. This energy consumption can be computed on an annual basis, using a simple formula. It's important to know that this formula is only valuable for as long as the fans are only used for hygienic ventilation. If the ventilation system is designed to contribute to room heating, the ventilation rate will be much higher than just hygienic ventilation and the fans will logically be dimensioned on that basis. The energy use in that last case will be higher. For this investigation, only fans for hygienic ventilation are taken into account. The energy use is to be calculated on a monthly basis and then summed over all months to result in an annual energy consumption for the fans.

Monthly based:

$$W_{aux,fans,vent,m} = t_m \; . \sum_{j} \Phi_{fans,vent,j} \quad 3{,}6 \qquad (4)$$

Annual based:

$$W_{aux,fans,vent,a} = \sum_{m} W_{aux,fans,vent,m} \qquad (5)$$

with:

t_m the length of the month in Megaseconds (Ms)

$\Phi_{fans,vent,j}$ the notional value for the mean electric power of fan j. This power is determined to be half of the maximum power of the electric motor, since it is not always in use.

2.3 Total investment cost calculations

For this investigation we approached some companies to make an offer for some ventilation systems. In the research, these offer prices are being used, because of the difficulty and the uncertainty of the calculation methods used by the companies. Asking for an offer from several companies to install the exact same system, can result in a lot of different cost estimations and a solution for this kind of problem needs to be found.

Price settings and price functions are difficult enough for simple materials like insulation, bricks, concrete slabs, windows… Trying to determine a total investment cost for a system (ventilation, heating, cooling…) even goes a little further. A system not only consists of a installation unit. Ducts, controllers, distribution elements, inlet openings… need to be calculated as well, to get a reliable investment cost. It's clear that these factors are different for each investigated building and may differ depending on the system design. Two companies installing the exact same system, will handle other calculation methods and perhaps other design rules relying on their own experiences. Specifically for ventilation systems, following prices need to be added to the investment cost of a ventilation unit:

- Ducts: depending on the distance between the room and the ventilation unit. Depending on whether a system C or system D is used, the amount of ducts may double or not.
- Fans: depending on the amount of fans that need to be installed and whether or not it's necessary to add extra fans.
- Supply and extraction grilles: depending on the system and the rooms that need to be provided with grilles.
- Controllers and measuring sensors: depending on the company, the desired precision of the system control, the amount of sensors and the amount of rooms that need to be controlled independently.
- Suspension systems and placement procedures: depending on the amount of ducts, ventilation units and grilles
- Balancing procedures and balancing time: depending on the companies procedures
- …

Because of the uncertainty of all these parameters, a total cost was set for every ventilation system, as presented in *Table 2: Investigated ventilation systems and their parameters for the calculation of the energy performance and the total investment cost*. The information in this table is drawn from several offers from companies and for each system the cheapest offer, off course being conform to the demand, is taken. Doing so, the calculation procedure for the cost of a ventilation system is no longer dependent on the approach of the investigator, but only on the approach of the offering company, exactly like it is in practice.

2.4 Optimization concept

To make an optimal choice for a ventilation system, one should decide on objective, numerical operations rather than on sheer gut feeling. To make an optimized decision upon energy consumption and total investment cost, simple common sense can offer some help. We all want the best we can get out of our invested money. In means of energy that means we want as much energy savings as possible and we want the investment cost to be as low as possible. A utopic situation for that matter would be where the energy savings are infinite, while there's no investment cost at all, or even better: we get paid for it. Every kind of investment should give the most energy saving possible for the lowest marginal cost. In mathematical terms, it's fair to say:

$$\text{Optimal theoretical solution} = \min \frac{\Delta IC_{T,i}}{-\Delta P_i} \quad (6)$$

with:

$\Delta IC_{T,i}$ the marginal investment cost for a ventilation systemi

$-\Delta P_i$ the decrease of the energy consumption due to ventilation systemi

In words, this means $\frac{\Delta IC_T}{-\Delta P}$ needs to be as small as can be. Only that solution is the optimal solution. Sometimes however, it's financially impossible to make the most optimal choice and then there's need for another solution to be chosen. In that case, the second lowest $\frac{\Delta IC_T}{-\Delta P}$ should be chosen and if that solution is financially insufficient, the third or the forth or…

Looking at *Table 2: Investigated ventilation systems and their parameters for the calculation of the energy performance and the total investment cost* and knowing you only have €1000 to spend, you always have to choose ventilation system C_{he}, no matter what. It's very probable that this solution is not the optimal one at all, but since there's no more money, it's the best there can be done. However, having €1500 at your expends, there's a decision to be made between ventilation systems C and C_{he}. System C requires a higher investment cost than system C_{he} and the investment is only justified if it makes the energy consumption drop more than system C_{he}. With some certainty it can be said that it does not, so it's smarter to choose ventilation system C_{he} and save €500. Let's however say, purely hypothetic, that ventilation system C does cause a bigger energy saving than ventilation system C_{he}. What has to be done then? This is the part, where $\frac{\Delta IC_T}{-\Delta P}$ becomes an important factor. To make a decision, $\frac{\Delta IC_T}{-\Delta P}$ has to be calculated for both ventilation systems. Only 3 situation can appear:

1) $\frac{\Delta IC_T}{-\Delta P}$ for ventilation system C is higher than $\frac{\Delta IC_T}{-\Delta P}$ for ventilation system C_{he}: Ventilation system C_{he} is the optimal solution and the decision is simple. C_{he} is chosen.
2) $\frac{\Delta IC_T}{-\Delta P}$ for ventilation system C is lower than $\frac{\Delta IC_T}{-\Delta P}$ for ventilation system C_{he}: Ventilation system C_{he} is not the optimal solution. At first ventilation system C is chosen because of it's lowest $\frac{\Delta IC_T}{-\Delta P}$. Afterwards a decision needs to be made whether it's necessary to restrict the energy consumption even more. If really required, ventilation system C_{he} has to be selected after all.
3) $\frac{\Delta IC_T}{-\Delta P}$ for ventilation system C equals $\frac{\Delta IC_T}{-\Delta P}$ for ventilation system C_{he}: Nothing can be said about the optimality of the ventilation systems. They are equally optimal, however unlikely. The decision now only depends on the need for energy reduction, since the energy performance and the investment cost for both systems are linearly related.

Mathematically spoken formula (6) can be rewritten for the real optimal solution as:

$$Optimal\ solution = \min\ \min\ \Delta IC_{T,i}\ , \min\ \frac{\Delta IC_{T,i}}{-\Delta P_i} \qquad (7)$$

with:

$\Delta IC_{T,i}$ the investment cost for a ventilation system i

$-\Delta P_i$ the decrease of the energy consumption due to ventilation system i

3 CASE STUDY

To illustrate this methodology for the choice of a ventilation system, a case study has been done, using all ventilation systems in *Table 2: Investigated ventilation systems and their parameters for the calculation of the energy performance and the total investment cost*. The investigated building is a two story, detached house with a flat roof. For the ventilation calculations a family consisting of 4 people is assumed. The dwelling has a net floor area of 308 m² and a volume of about 1030 m³.

As a reference situation, the investigated case study house has been insulated up to a mean value for U of 0.4 W/m².K. Achieving a compactness of 1.49, this value results in an overall K-value of 34. The reference case has no ventilation system.

Assume in this case, a ventilation system needs to be installed, because of the bad air quality in the dwelling due to unventilated rooms. Doing some calculations with the data subtracted from *Table 2: Investigated ventilation systems and their parameters for the calculation of the energy performance and the total investment cost*, a well-founded decision can be made. The results from the calculation are collected together in

Table 3: Results of the calculations of investment costs and energy performance improvements for a list of ventilation systems applied to a case study house.

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Ventilation system	IC_T [€]	ΔIC_T [€]	P [W]	-ΔP [W]	$\frac{\Delta IC_T}{-\Delta P}$ [€/W]
0	€ 344.059		4158,4		
C	€ 345.559	€ 1.500	4191,7	-33,3	-45,05
C_{he}	€ 345.059	€ 1.000	4076,9	81,5	12,27
C^+	€ 347.359	€ 3.300	4042,6	115,8	28,50
D^+	€ 348.059	€ 4.000	4019,2	139,2	28,74
D_{he}	€ 349.059	€ 5.000	3589,9	568,5	8,80

The information in

Table 3: Results of the calculations of investment costs and energy performance improvements for a list of ventilation systems applied to a case study house makes it possible to decide which ventilation system to choose in the case study house. Making the simplest analysis possible at first, nobody in his right mind would choose ventilation system C. It's clear that the energy consumption for ventilation system C exceeds the energy consumption for no ventilation system at all. However, in this regard, an objection needs to be made, since a ventilation system causes an improvement of the indoor air quality. System C will perhaps not result in an energy reduction, it will make the inner environment more comfortable.

Taking into account the decision steps described in2.4Optimization concept, the path that needs to be followed is this:

1) The most optimal ventilation system would be system D_{he}. It has a $\frac{\Delta IC_T}{-\Delta P}$ of 8.8 and that's the lowest that can be found in the table. The cost however is € 5.000 and that's quite a high cost.
2) The next optimal ventilation system is ventilation system C_{he}, with a $\frac{\Delta IC_T}{-\Delta P}$ of 12.27. It only costs € 1.000 and that's the lowest investment cost in the table. Ventilation system C_{he} would be the best choice to make at first.
3) If ventilation system C_{he} doesn't imply a big enough reduction of the energy use and still some money is left to spend, the next system in line would be ventilation system C^+. $\frac{\Delta IC_T}{-\Delta P}$ of that system is 28.50 and it requires a spend of € 3.300, still less than € 5.000 for the most optimal solution.
4) If ventilation system C^+ doesn't fit the expectations in means of energy reduction, next system to choose would be ventilation system D^+, with a $\frac{\Delta IC_T}{-\Delta P}$ of 28.74 and an investment cost of € 4.000, still less than € 5.000 for system D_{he}.

In short, that means ventilation system C is not to be chosen. It is Pareto dominated by ventilation system C_{he}, because it causes a bigger energy use reduction at a cheaper price. Choosing ventilation system C, wouldn't be the smartest thing to do. In Figure 1: Graph of the optimized decision model for a ventilation system, the decision making process is illustrated through a graph, where the objective on the x-axis is the ventilation system. On the upper y-axis, $\frac{\Delta IC_T}{-\Delta P}$ for all ventilation systems can be read and on the lower y-axis the additional cost with respect to the reference case.

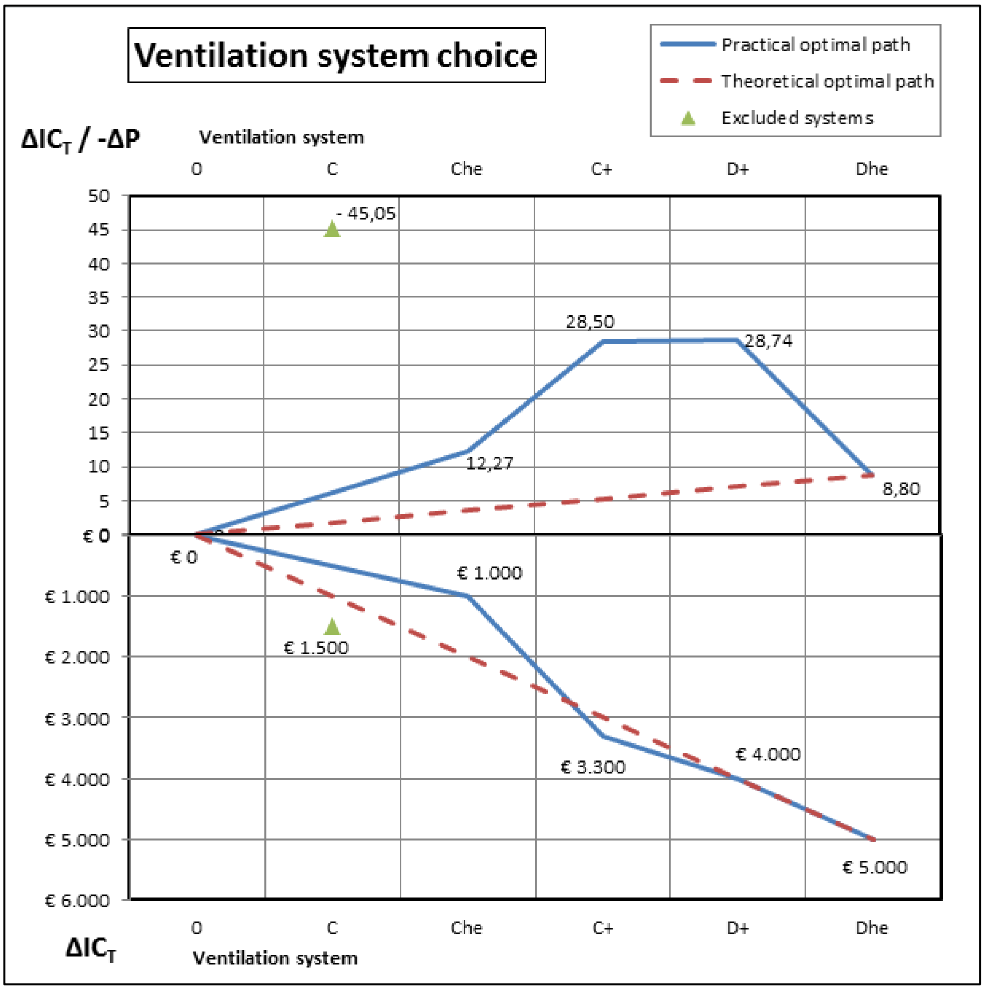

Figure 1: Graph of the optimized decision model for a ventilation system

with:

- The theoretical optimal path being the decision made when marginal investment cost doesn't matter. It is the same decision that would be made if the ventilation system was a continuous variable instead of a discrete parameter.
- The practical optimal path being the sequence of decisions made knowing the marginal investment cost may have some importance.

4 CONCLUSIONS AND DISCUSSION

The choice of a ventilation system for nearly zero energy buildings is a multi-objective problem. On one hand, the energy consumption on annual basis needs to be reduced as much as possible. On the other hand the investment cost has to be kept as low as possible. These 2 objectives are conflicting: energy reduction almost always implies an increase of the investment cost. The proposed method for the selection of a ventilation system out of a list, generates a Pareto optimal line consisting of non-dominated solutions. At that point, ventilation system drops out for the studied case. It's however important to know that a ventilation system C for another case or from another company or distributor can be optimal.

An important conclusion here can be that all ventilation systems in Table 2: Investigated ventilation systems and their parameters for the calculation of the energy performance and the total investment cost are handled with respect to each other. The list is off course non-limitative and new systems, extra systems, systems from different companies can be added as well and will be dealt with the same.

In this investigation, only ventilation systems are being optimized, but imagine what would happen when the insulation thicknesses, the airtightness, the window types, the lighting systems… are taken into account. It's not inconceivable that an additional centimeter of insulation causes a higher energy reduction at a lower price. In that case the insulation thickness dominates the ventilation system. This path is a very interesting one to follow. It means that perhaps it would be better first to insulate the building and then after a while decide to change the ventilation system.

Same thing can be said about the discrete characteristics of the ventilation systems. The investment cost for example takes jumps of about € 1.000. Between 2 systems, addition insulation measures can be taken, especially when the investment cost for the next ventilation system in line is too high.

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