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IMPLEMENTATION OF EXERGY –CALCULATIONS IN AN EXISTING SOFTWARE TOOL FOR ENERGY-FLOW CALCULATIONS IN THE EARLY DESIGN STAGE

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ABSTRACT

This paper focuses initially on the calculation of the flows of exergy corresponding to the energy demand of buildings for the following uses: heating and cooling in the air handling units, local (room level) heating and cooling, lighting, ventilators and electrical appliances. The calculation method is presented as well as its implementation in the existing energy-calculation software. The effect of the temperature of the supply system for heat and cold is discussed.

The paper then deals with the exergy delivery at room level, with the exergy consumption at the meter box and with the final building exergy consumption. The exergy demand is based purely on physical balances between the building being maintained at a defined level of comfort and its environment, whereas the final exergy consumption is dependent on the type and efficiency of the energy distribution and generation systems. The method used to estimate the exergy delivery at room level, the exergy consumption at the meter box and the final exergy consumption in the early design stage is explained. Initial conclusions are drawn about the discrepancies between the exergy demand of the building and its final exergy consumption on one hand, and about the discrepancies between the energy analysis and the exergy analysis on the other.

INTRODUCTION

Considerable efforts have been made in the past to simulate energy flows in buildings in order to predict and reduce their energy consumption. Specific attention has also been paid by several authors ((Hensen, 1993), (BDA, 2000), (IEA, 2001), (Energy Plus, 2003), (Yezioro, 2003), (Itard, 2003)) to the specific needs for simulation in the early design stage. In this stage, simulations are aimed at taking design decisions for the building and its installations on the basis of the little data that is available at the start of a project. The present paper focuses on exergy analysis in the first design stage, as a method of increasing the sustainability of buildings. Exergy is the quality of energy and, according to the second law of thermodynamics, is the quantity that is consumed during processes.

Energy itself is never consumed, but always conserved. Earlier studies have been conducted on exergy analysis in buildings ((Shukuya et al., 2002), (Asada, 1996), (Schmidt, 2003), (Boelman, 2004) among others) in which several processes related to the building are analysed. The present paper does not focus on a detailed analysis of some constituent processes within a building, but rather on a more general comparison of all significant processes. This approach was chosen to identify which measures should first be taken to increase the sustainability of buildings.

To achieve this work, the h.e.n.k. software tool for the early design was used (Itard, 1999) and (Itard, 2003). Calculations in this software tool are based on semi-dynamical calculations and hourly weather data for one year. The implementation of exergy calculations in this energy-calculation software will be described and examples will be given for the typical oceanic climate of the Netherlands.

ENERGY DEMAND, CONSUMPTION AT THE METER BOX, PRIMARY ENERGY CONSUMPTION AND EXERGY

The energy demand of a building is based purely on physical balances between the building maintained at a defined level of comfort and its environment. When defining the energy or exergy demand, it is important to consider both the physical aspects of a building and its uses. This is because the ways in which a building is used influence the internal heat load and the lighting and power demand considerably. All relevant energy items should be taken into account to avoid focusing on a single aspect of the energy demand, which could lead to erroneous assumptions about energy savings. For instance, adding insulation decreases heat demand but increases cooling demand, while having fewer windows decreases heat demand, but increases lighting demand.

The energy consumption at the meter box is the exergy used by the equipment located in the building, such as boilers, cooling machines, piping and electrical appliances. It is the energy, which has to be paid by the owner or tenant to the electricity or gas company. As such, it is an important parameter of the design process because it

determines the payback time of the designed building and equipment.

The primary energy consumption is the final energy consumption of the entire chain, including energy generation and transport systems outside the building.

When designing buildings and their equipment, it is important to analyse these three steps in order to make the appropriate choices: the equipment should match the demand. However, one should keep in mind that a minimum in the energy demand does not necessarily lead to a minimum in the final energy consumption. This is because of the different efficiencies of the energy conversion equipment. For instance, a non-optimal energy demand in which the cooling demand is very high could produce optimal primary energy consumption because energy storage in the ground is used. This stresses the importance of an analysis of the whole chain and of a description of the relevant processes that is as complete as possible.

When considering exergy analysis, it would appear that the three steps described above are insufficient to describe the exergy chain. A forth step must be included between the demand and the use at the meter box. This is because exergy is related to the temperature at which energy is delivered. This temperature has neither an effect on the energy demand nor on the energy use at the meter box, but is crucial to the determination of the irreversibility. In this paper, the term 'exergy delivery' is used to describe this step.
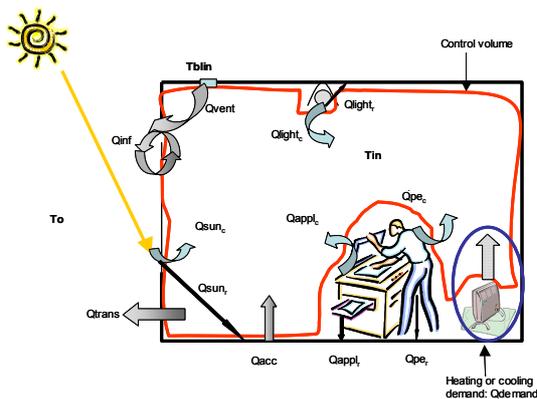
ENERGY DEMAND AND RELATED EXERGY LOSSES

Figure 1 The control volume for the heat and cold demand in the building

The system studied is described in Figure 1. Heat is added to the control volume by lighting, people and appliances. Air flows into and out of the control volume through infiltration and ventilation. If the ventilation air is first treated in an air-handling unit, the temperature of the air flowing into the control volume (T_{blin}) is different from the outdoor temperature To. The total energy demand consists of eight items:

- Demand for heat in the building (seen in this paper as a room)
- Demand for cold in the building (seen in this paper as a room)
- Demand for heat in the air handling system
- Demand for cold in the air handling system
- Demand for moisture in the air handling system. This item has not been covered in the present study
- Demand for lighting
- Demand for ventilators should there be mechanical ventilation
- Demand for appliances such as computers and servers.

Energy demand for heating and cooling

The model for the heat and cold balances within the building envelope is based on hourly energy balances taking into account the following processes:

- Transmission (Qtrans) across walls and windows, based on the outdoor and indoor air temperature, inclusive of correction for radiation losses. The desired indoor air temperature depends on the opening times of the building.
$$Qtrans = \sum -U.A.(T_{in} - T_o) \quad (1)$$
where the summation is on all building parts (facades, windows, roof and floors).

- Air infiltration (Qinf), based on a constant infiltration rate and on the outdoor and indoor air temperatures.
$$Q\inf = -m_{\inf}.C_p(T_{in} - T_o) \quad (2)$$

- Ventilation (Qvent), based on ventilation rates depending on the hourly occupancy rate, on the indoor temperature Tin and on the air supply temperature Tblin.
$$Qvent = -m_{vent}.C_p(T_{blin} - T_{in}) \quad (3)$$

- Sun entering the building and being directly transmitted by convection to the indoor air after absorption in the glass panels (Qsun $_c$), based on hourly values of the sun radiation on the window, on the heat transmission factor and on the convection coefficient.

- Heat load through equipment and appliances (Qappl $_c$), people (Qpe $_c$) and artificial lighting (Qlight $_c$), depending on the hourly occupancy

rate and the respective coefficients of convection. The following assumptions have been made for calculating these heat loads:

- o The installed electrical load of appliances, in watts per square meter, is known from the program of requirements or from earlier experience. The hourly load is then calculated, depending on occupancy profiles. The whole power is finally converted to heat and is partly rejected to air ($Qapp_c$) and partly absorbed by the construction ($Qapp_r$).
- o The heat load from people is calculated from occupancy profiles and from the sensible and latent heat of persons, depending on Clo-values, metabolism and indoor air temperature. The whole load is finally converted to heat and is partly rejected to air (Qpe_c) and partly absorbed by the construction (Qpe_r).
- o A constant electrical power per square meter is assumed for lighting. The whole power is finally converted to heat and is partly rejected to air ($Qlight_c$) and partly absorbed by the construction ($Qlight_r$).
  The surface area that must be lighted is determined hourly by calculation of the depth of penetration of sunlight into the building. The area where the sunlight produces a lighting intensity higher than the wanted intensity (for instance 400 lux), is not lighted artificially.

- Heat from heat accumulation in the construction (Qacc). The heat accumulated consists of the part of the sun radiation, of the heat from appliances, people and artificial lighting that has not been directly transmitted to the air, but that has been absorbed by the construction ($Qsun_r$, $Qappl_r$, Qpe_r, $Qlight_r$). This heat is given back to the room air with a delay. The method of the response factor (van Paassen, 1981) is used to calculate the part of the heat that is given back hourly to the room. Qacc is a function of the thermal mass of the building, of its physical properties, of the outside temperature and of the heat absorbed by the construction.

The hourly energy balance of the building is given in equation 4 and allows determining the energy demand of the building (equation 5):

$$Q_{in} - Q_{out} = 0 \qquad (4)$$

$$Qdemand = Qtrans + Q\inf + Qvent + Qlight_c + \\ Qpe_c + Qappl_c + Qsun_c + Qacc \qquad (5)$$

Depending on the relative outdoor and indoor temperatures, Qtrans, Qinf and Qvent are positive or negative. Qlight_c, Qpe_c, and Qappl_c and Qacc are always positive. When Qdemand is negative, there is a heating demand (Qheatdem=|Qdemand|). When Qdemand is positive, there is a cooling demand (Qcooldem=Qdemand).

Exergy losses corresponding to the energy flows playing a role in the energy balance at building level.

The exergy demand is calculated using the assumptions described above. According to (Brodyansky, 1994) and (Shukuya, 2002), the exergy balance on the control volume is

$$E_{in} + E_{generated} = E_{out} + E_{lost} \qquad (6)$$

By considering that no entropy is generated inside the control volume (there are no chemical reactions), the balance can be reduced to

$$E_{in} - E_{out} = E_{lost} \qquad (7)$$

When the temperature at which a process takes place is higher than the outside air temperature, the control volume is fed with exergy. When the temperature is lower than the outside temperature, exergy is flowing out of the system.

The exergy is calculated by using equation 8.

$$dE = dH - TodS = dQ + VdP - To\frac{dQ}{T} \qquad (8)$$

Under the assumption of constant pressure, the exergy becomes:

$$dE = dQ(1 - \frac{To}{T}) \qquad (9)$$

If dQ is independent of the indoor temperature, the exergy is (see Schmidt, 2004):

$$\Delta E = \Delta Q(1 - \frac{To}{T}) \qquad (10)$$

If dQ is a linear function of the temperature (dQ=f.dT), the integration of equation 10 leads to (see Shukuya, 2002):

$$\Delta E = f.(T_2 - T_1 - ToLn\frac{T_2}{T_1}) \\ = \Delta Q(1 - .\frac{To}{T_2 - T_1}.Ln\frac{T_2}{T_1}) \qquad (11)$$

The calculations use the following assumptions:

- For transmission, infiltration and ventilation equation 11 is used.

$$Etrans = Qtrans(1 - \frac{To}{Tin - To}.Ln\frac{Tin}{To}) \quad (12)$$

$$Einf = Qinf(1 - \frac{To}{Tin - To}.Ln\frac{Tin}{To}) \quad (13)$$

$$Event = Qvent(1 - \frac{To}{Tblin - To}.Ln\frac{Tblin}{To}) \quad (14)$$

- The heat released by the construction into the room is assumed to be at room temperature.

$$Eacc = Qacc.(1 - \frac{To}{Tin}) \quad (15)$$

- The heat produced by people is assumed to be at the skin temperature of 306 K

$$Epec = Qpec.(1 - \frac{To}{306}) \quad (16)$$

- The heat produced by the lighting is assumed to be at 6000 K (temperature of white light), as well as the heat from the sun heat entering the building.

$$Elightc = Qlightc.(1 - \frac{To}{6000}) \quad (17)$$

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$$Esunc = Qsunc.(1 - \frac{To}{6000}) \quad (18)$$

- The heat produced by appliances such as computers and printers is assumed to be at a temperature of 40^{0}C.

$$Eapplc = Qapplc.(1 - \frac{To}{313}) \quad (19)$$

- The exergy produced by the ventilator is equal to its energy use.

$$Event = Qvent \quad (20)$$

- In an ideal case, the heating and cooling demands are supplied at room temperature (see also (Schmidt, 2004) by local heating or cooling equipment:

$$Eheatdem = Qheatdem(1 - \frac{To}{Tin}) \quad (21)$$

$$Ecooldem = \left| -Qcooldem(1 - \frac{To}{Tin}) \right| \quad (22)$$

Energy and exergy demands for air heating and cooling in the air-handling unit

The previous section studied the energy and exergy flows inside the control volume. The air-handling unit does not belong to this control volume and is therefore studied in the present section. The air in the air-handling unit is heated or cooled from To to Tblin.

$$Qvent_{ahu} = m_{vent}.C_p(T_{blin} - To) \quad (23)$$

$$Event_{ahu} = Qvent_{ahu}(1 - \frac{To}{Tblin - To}Ln\frac{Tblin}{To}) \quad (24)$$

Energy and exergy demand for electrical appliances (lighting, ventilators and appliances)

The energy demand of all electrical appliances is calculated using the net surface area and the specific needed capacity per square meter, which is known from the program of requirements or from experience. The exergetic efficiency is 1, therefore

$$Elight_e = Qlight_e$$
$$Eventil_e = Qventil_e \quad (25)$$
$$Eappl_e = Qappl_e$$

Results for the test-case of an office building
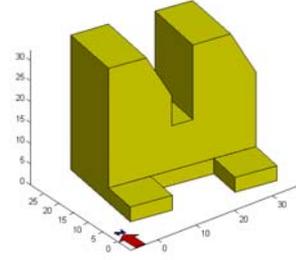
The reference building

Figure 2 The envelope of the simulated building

The simulated office building is represented in Figure 2. The gross floor area is 4350m^2. The Rc-values are 2.5 Km^2/W for all facades, floors and roofs, windows excluded. All facades have 40% windows, with an U-value of 1.8 W/Km^2, a heat transmission coefficient of 0.3 and a light transmission coefficient of 0.6. The convection factor for lighting, people and appliances is 0.5 and the convection factor for sun radiation is 0.024. The maximum occupancy rate is 1 person for 20 m^2. This rate varies during the day, according to the opening times of the building (7:00 to 18:00 hour, 5 days a week). The infiltration rate is 0.5 (m^3/hour)/m^3, the natural ventilation rate is 3 (m^3/hour)/m^3. For the appliances, it is assumed that a power of 10 W/m^2 is needed. The building's active thermal mass is about 200 kg/m^2. A light intensity of 450 Lux is required at desk level. The
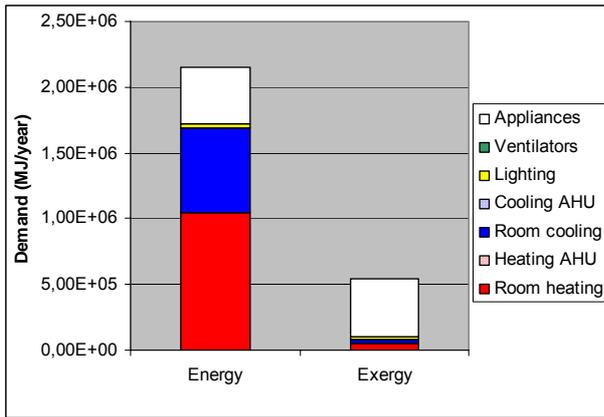
Figure 3: Comparison between the energy and exergy demands for the reference building (total for one year, no demand for ventilators or AHU).
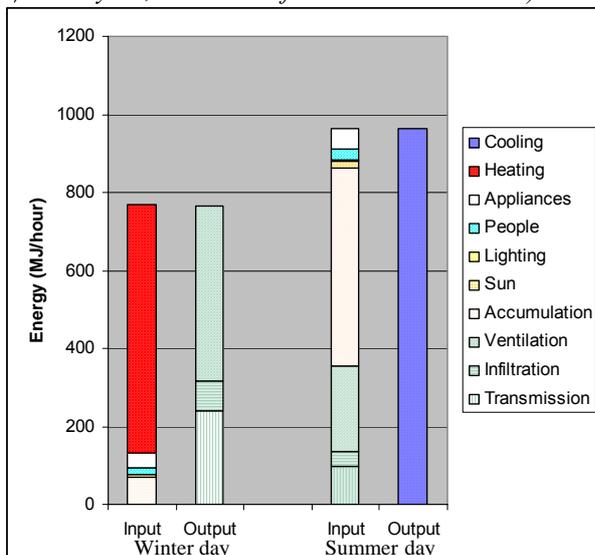

Figure 4: Energy flows for all processes taken into account in the balance on the control volume. Left: winter day(586th hour of year, outside temp.: 5 ^{0}C). Right: summer day(4455th hour of year, outside temp.: 31.6 ^{0}C).
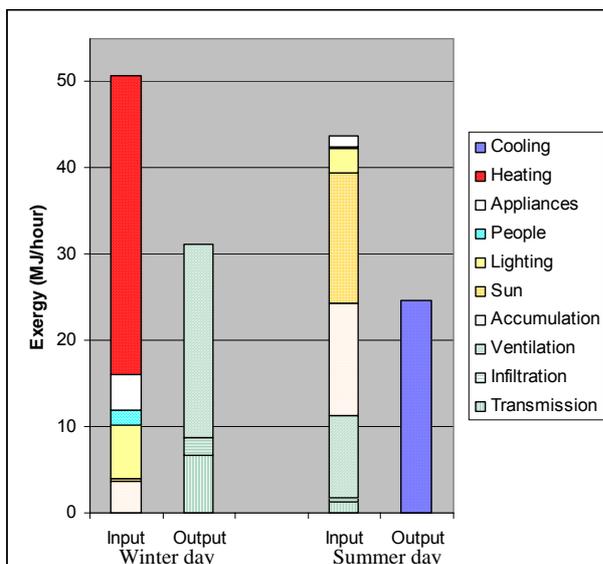

Figure 5: Exergy flows for all processes taken into account in the balance on the control volume (same hours and temperature as in Figure 4).

lighting equipment has a specific capacity of 1.8 W/m^2, which corresponds to ideal lighting, achieved by white sunlight, which has an intensity of 250 Lumen/W (Delbruck, 1997), that is 4e^{-3} W/(m^2.Lux). This means in the present case that a power of 1.8 W/m^2 is enough to ensure sufficient lighting.

Simulations have been made for one typical climate year in the Netherlands, by means of a TRY-year, using hourly weather data. Figure 3 shows the total energy and exergy demands of the reference building for one year. The heating of the building accounts for approximately half of the energy use, but the related exergy losses are almost negligible when compared with the exergy losses related to appliances. This means that passive measures should preferably be aimed at reducing the demands of power for appliances rather than at further insulating the building.

Figures 4 and 5 show the energy and exergy flows through the control volume (see Figure 1) in more detail. The left-hand side of the graphics represents one hour of a winter day, while the right-hand side shows one hour of a summer day. The input takes into account all flows coming into the control volume. The output includes all flows going out of the control volume. The calculations of the exergy assume that heating and cooling are provided at room temperature. Figure 4 shows that energy is conserved and Figure 5 shows that exergy is lost. Although the lighting demand is very low, lighting appears to play a role in the irreversibility inside the control volume.

Parametric study of the energy and exergy demands
In this section, the energy and exergy demands of the reference building are compared with three different options:
- A building with a larger ventilation rate when cooling is needed (10 (m^3/hour)/m^3 instead of 3).
- A building in which a realistic, non-ideal power of 10 W/m^2 is applied for lighting.
- A building with mechanical ventilation instead of natural ventilation. The ventilation rate is still 3 (m^3/hour)/m^3. The air supply temperature depends on the outside temperature. When To is lower than 10^{0}C, Tblin is equal to 18^{0}C. When To is higher than 18^{0}C, Tblin is equal to 14^{0}C. In between a linear interpolation is used.

Figure 6 shows the results for the energy demand and Figure 7 the results for the exergy demand. The main energy demand of the building studied is needed for heating, whereas the main exergy demand is needed for electrical appliances. The effect of higher ventilation rates and more efficient lighting are both more efficient from the exergetic
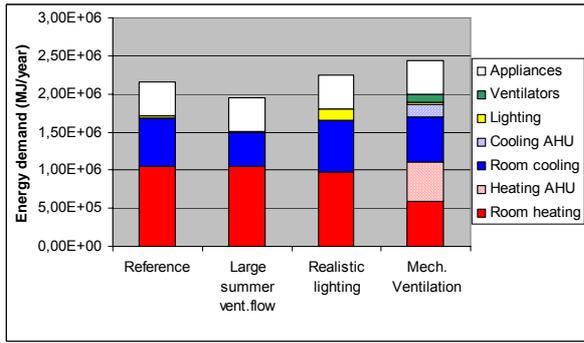
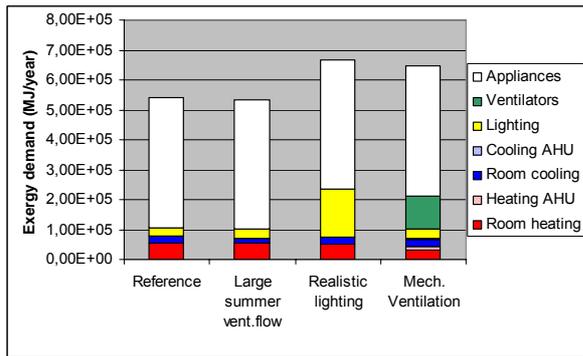*Figure 6: Energy demand for the reference and three options.*

Figure 7: Exergy demand for the reference and three options.

point of view than from the energetic point of view. Because the heating and cooling of air in the air-handling unit, when mechanical ventilation is applied, happens at temperature relatively close to the outside temperature, the related exergy losses are minimal. The exergy losses for the ventilators are high, however.

EXERGY DELIVERY

At a constant energy demand, the exergy losses are dependent on the temperature at which heating and cooling are supplied. The same equations as for the calculation of the exergy demand are used, but Tin is replaced by T_{supply} in equations 21 and 22. For this study, the building with realistic lighting (10 W/m^2) is used. Other data are the same as in the reference building. Two cases are studied.
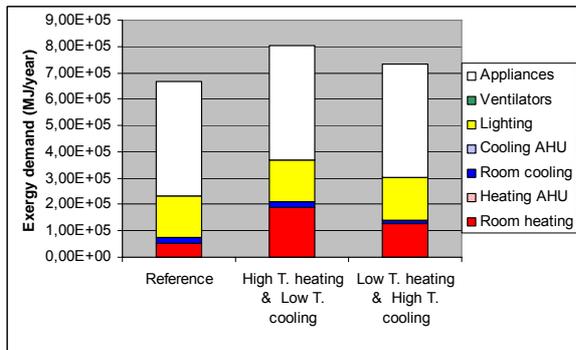

Figure 8: Effect of the supply temperature of the heating and cooling system on the exergy losses

In the first case, it is assumed that heating is supplied to the room at 70°C, and cooling at 8°C. In the second case, low temperature heating and high temperature cooling are applied. Heating is supplied at 45°C, and cooling at 15°C.

Figure 8 shows that the effect of the temperature supply on the exergy losses is significant, mainly for the heating system. A minimal effect is observed for the cooling system. This is because the temperature of the cooling system is always closer to the outside temperature than the temperature of the heating system. Because of the high internal heat load of office buildings, cooling is also needed whereas the outdoor temperature is lower than the indoor temperature. In this case, the use of equation 22 should be discussed.

ENERGY AND EXERGY CONSUMPTION AT THE METER BOX

The energy consumption at the meter box is the energy delivered to the system. The system comprises the room with heating and cooling system, the air-handling unit with ventilators and heating and cooling system and the electrical appliances, lighting included. Two heating and cooling systems have been studied:

- A high efficiency boiler and its distribution system (η=0.85) and a compression cooling machine with a COP of 3 (η=3).
- A heat pump with a COP of 4(η=4) in combination with cold storage in the ground ((η=12)).
- For lighting, ventilators and appliances, an efficiency of 1 is assumed.

The energy consumption at the meter box is then:

$$Qcons = \frac{Qdemand}{\eta} \qquad (26)$$

An exergetic efficiency of 1 is assumed for all terms. This means that losses in the electrical distribution system are neglected and that the combustion of gas in the boiler is assumed to take place at temperature infinitely high.

$$Econs = Qcons \qquad (27)$$

PRIMARY ENERGY AND EXERGY CONSUMPTION

The primary energy consumption is obtained by taking into account the efficiency of energy generation outside the building.

$$Qprim = \frac{Qcons}{\eta prim} \qquad (28)$$

For a gas boiler, η_{prim} is assumed to be one because the power generation takes place within the building. For all other energy generation systems (heat pump, compression cooling machine and cold storage), electricity is needed. It is assumed that the efficiency of electricity generation is 0.4, which is the average of power plants in the Netherlands. The exergetic efficiency for electricity generation is considered to be one ($E_{prim}=Q_{prim}$).

Figure 9 compares the energy demand and delivery, the energy at the meter box and the primary energy consumption of the system {high efficiency boiler / compression cooling machine}. The same comparison is done in Figure 10 for the exergy. From the energy point of view, the generation of heat is efficient, whereas it is very inefficient from
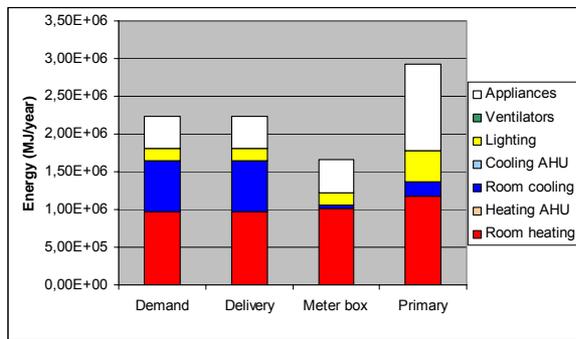

Figure 9: Energy demand & delivery, energy consumption at the meter box and primary energy use when using a boiler and a cooling machine.
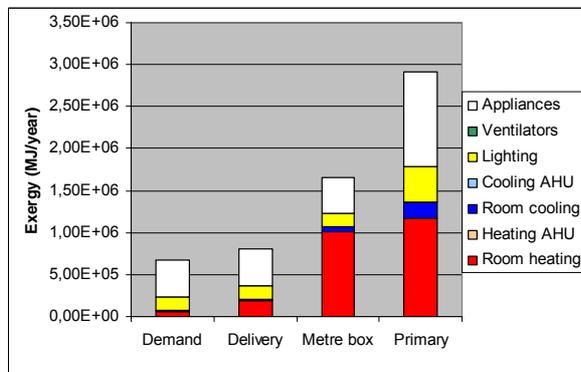

Figure 10: Exergy demand & delivery, exergy consumption at the meter box and primary exergy use when using a boiler and a cooling machine.

the exergetic point of view. This is because of the mismatch between the high temperature used in the boiler (T=2000K) and the low temperature needed in the room. Cooling generation is more efficient because no such high temperature is needed.

The same comparisons are made in Figures 11 and 12, this time for a system using a heat pump and cold storage. The irreversibility due to the generation of heat substantially decreases when applying low temperature heating.
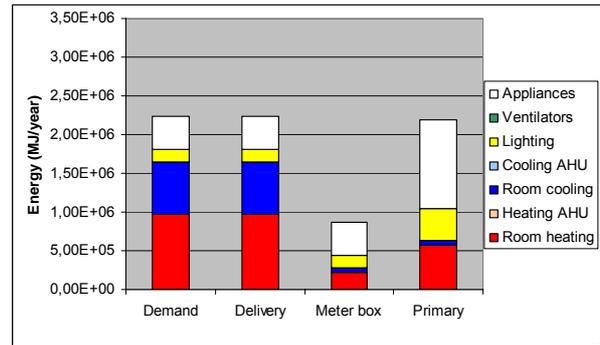

Figure 11: Energy demand & delivery, energy consumption at the meter box and primary energy use when using a heat pump and cold storage.
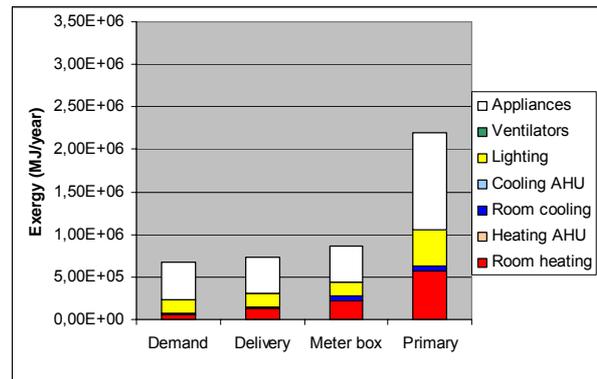

Figure 12: Exergy demand & delivery, exergy consumption at the meter box and primary exergy use when using a heat pump and cold storage.

CONCLUSIONS AND RECOMMENDATIONS

For this paper, a method was proposed to calculate the exergy flows within a building. The method has been implemented in the existing software tool for the early design, h.e.n.k.. First results were presented showing that:

- The exergy demand for heating in buildings is very low, but the irreversibility in the heating equipment is very high. More attention should therefore be paid to reducing this irreversibility (for instance by low temperature heating rather than by extreme insulation measures).
- In office buildings, the electrical demand for appliances is very high. In the present state of the art it would be more efficient to take measures to reduce this demand rather than to take measures affecting the building envelope.

In this study the importance of taking into account all energy and exergy items has been demonstrated rather than focusing on one specific aspect. However more research is needed on the internal irreversibility within the building. The irreversibility of the energy generation systems was taken into account simply, by means of energy and

exergy efficiencies. Here too, more research is needed to determine the extend to which this simplification is really acceptable.

SYMBOLS

Upper-case

$E (=\Delta E)$: Exergy (J/K)
$Q (=\Delta Q)$: Energy (J)
T: Temperature (K)

Lower-case / subscripts

acc: accumulation in the construction
ahu: air handling unit
appl: appliances (computer, printers etc…)
bin: indoor (temperature)
blin: air supply into the room
c: convective part
cons: energy or exergy consumption of the delivery system
Cp: heat capacity air (J/KgK)
e: electrical
inf: infiltration
light: lighting
m: air flow (kg/s)
o: outside (temperature)
pe: people
prim: primary (energy, exergy)
r: radiation part, accumulated in construction
sun: sun radiation entering the building
trans: transmission
vent: ventilation
ventil: ventilators
η: efficiency of   heating, cooling and electrical equipment within the building
ηp: efficiency of energy generation outside the building (power station)

ACKNOWLEDGEMENT

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