$4\ 554(20 - -16) = 164 \times 10^3$ kJ/h

This will cost $(164 \times 10^3 : 3\ 600) \times 0.3 = 13.66$ SEK/h, if the energy price is 0.3 SEK/kWh. Thus, it is necessary to include the ventilation equipment in the energy retrofit strategy. Indeed it would be profitable to deminute the ventilation flow or to take care of the heat in the ventilation air using heat exchangers or ventilation air heat pumps.

4.1.5.2 Ventilation equipment. Retrofit cost

For ordinary natural ventilation systems there are very low costs for the maintenance of the channels or pipes in the chimney. The ineviteable retrofit cost consists of cleaning the pipes from dust etc. I have found 2 references dealing with this type of cost (43) and (44). Unfortunately, these are written in Swedish and they deal mostly with mechanical ventilation systems. In the literature I have found no necessity for measures on a natural system that can imply on the profit of energy retrofits, so in my case it is assumed that there is no existent retrofit cost at all.

4.1.5.2.1 The ventilation equipment, sealing and caulking windows and doors

One way to make the energy cost less is to make the ventilation flow lower. In Sweden, however, there is a limit for this measure, because the ventilation system must be able to provide a flow of 0.35 l/s, m^2 (5 p 246). This value corresponds to about 0.5 renewals/hour. (0.35 l/s m^2 = 1 260 m^3/h m^2. Each m^2 of the dwelling area corresponds to 2.4 x 1 = 2.4 m^3 air in the room. 1 260 : 2.4 = 0.525 l/h). If the natural ventilation equipment has a higher flow it can be a profitable solution to caulk the windows and doors to come down to this limit. It shall be noted here that the code only tells us that it should be possible to ventilate with 0.35 l/s, m^2. It is not necessary to do this all the time. However, it has been found that caulking diminutes the natural ventilation flow with about 0.3 renewals per hour, (45) and in my case this results in a flow of 0.5 renewals/hour. If there was a higher existent ventilation flow it probably would be profitable to throttle the flow in the terminal device. The cost for caulking the windows is here assumed to be of the magnitude 200 SEK for each window. In my case there is 30 + 30 + + 12 + 12 = 84 windows, 20 apartment doors and 6 other doors. The cost for caulking these is therefore:

$$RC_c = 110 \times 200 = 22\ 000 \text{ SEK, where:} \qquad \text{(F30)}$$

RC_c = Retrofit cost for caulking (F30).

4.1.5.2.2 The ventilation equipment. Exhaust air heat pump

With a heat pump using the exhaust air as a heat source it is possible to bring back some of the energy to the building. In many cases this heat is used to produce tapwater. However, there is not always a need in this sink and thus it will be a better profitability if the heat also is used for the thermal climate in the building. This utility makes the heatpump work almost all the time, at least in the winter period (61 p 18 -). This kind of equipment is often used in new single-family houses, but the experiences are much less from installing heat pumps in existent multi-family buildings. It is not so hard to find the different prices for heatpumps from the manufacturers, but the problems are greater finding information about the costs for equipment installed in existent buildings. In (46 p 42 - 92) 10 different installations have been tested, some of them installed in old houses. The costs for the installation (including the heat pump) are depicted in Figure 20.

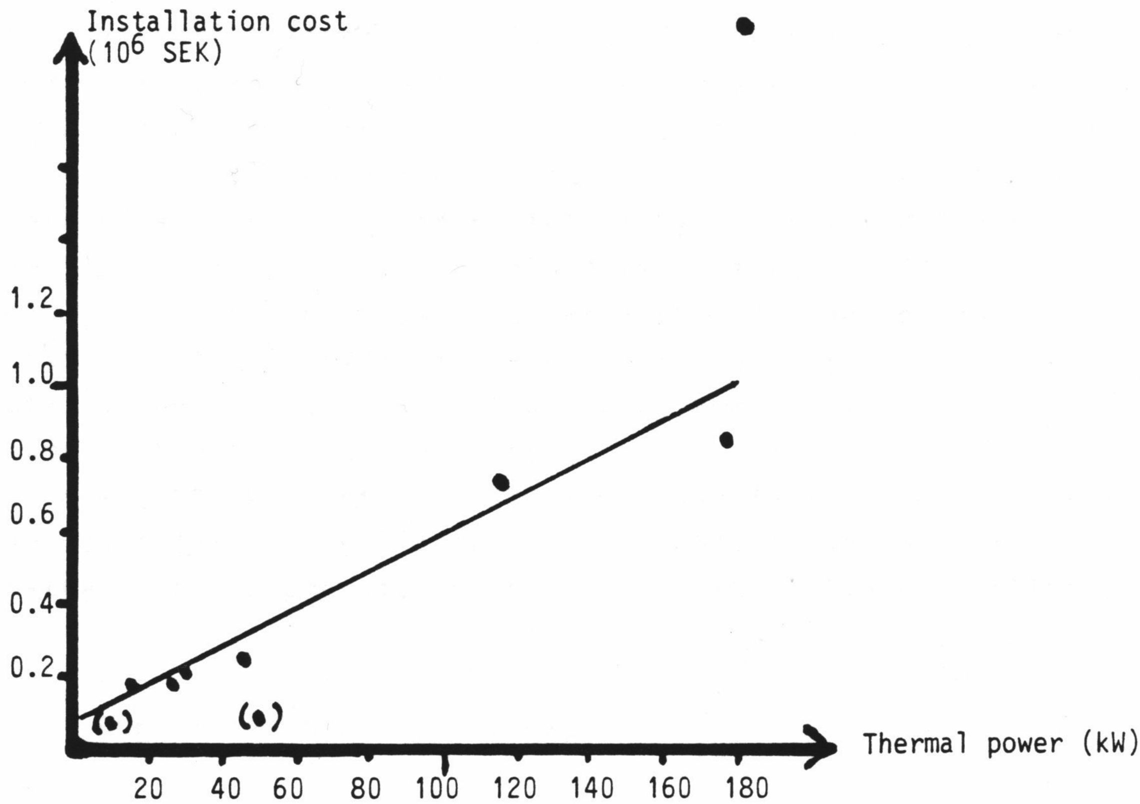

Figure 20. Installation cost for exhaust air heat pumps (45).

A mathematical expression for the installation cost can be calculated as:

$$RC_{EH} = 90\ 000 + 5\ 000 \times P_{EH} \qquad (F31)$$

where RC_{EH} = Retrofit Cost Exhaust air Heat pump
P_{EH} = Thermal Power Exhaust air heat pump

It shall be noted here that there is a lack of experience exactly how the heat pump in the best way shall be connected to the existing heating system in the house, (46 p 12).

There have also been a lot of problems with the heatpump systems. Mostly these depends on calculating with errors in ventilation flow and exhaust air temperature. In (46 p 33) it is mentioned that it is not uncommon with an exhaust air temperature of 14 °C in the wintertime. This because of leaking air pipes or connections to the refuse chutes.

Several installations are also working with a too small temperature difference between the in- and outlet in the air flow through the device. In (46 p 8) it is mentioned that an optimal outlet temperature should be -3 °C. The problem with leaking air channels can be solved by different methods. Smaller pipes put into the old ones cost about 120 SEK/m, while caulking the pipes with an asphalt rubber compound costs about 450 SEK/m (47). In (48 p 184 - 185) the installation cost for exhaust air heat pump is shown. A heat pump with a power of 50 kW costs about 155 00 SEK and another, 190 kW costs 235 000 SEK. Exactly how these figures are calculated is not evident from (48). An approximative mathematical expression calculated on these figures will be:

$$RC_{EH} = 126\ 500 + 570 \times P_{EH} \qquad (F32)$$

In (49 p 34) the installation costs for 13 exhaust air heat-pumps are shown. These figures are depicted in Figure 21.

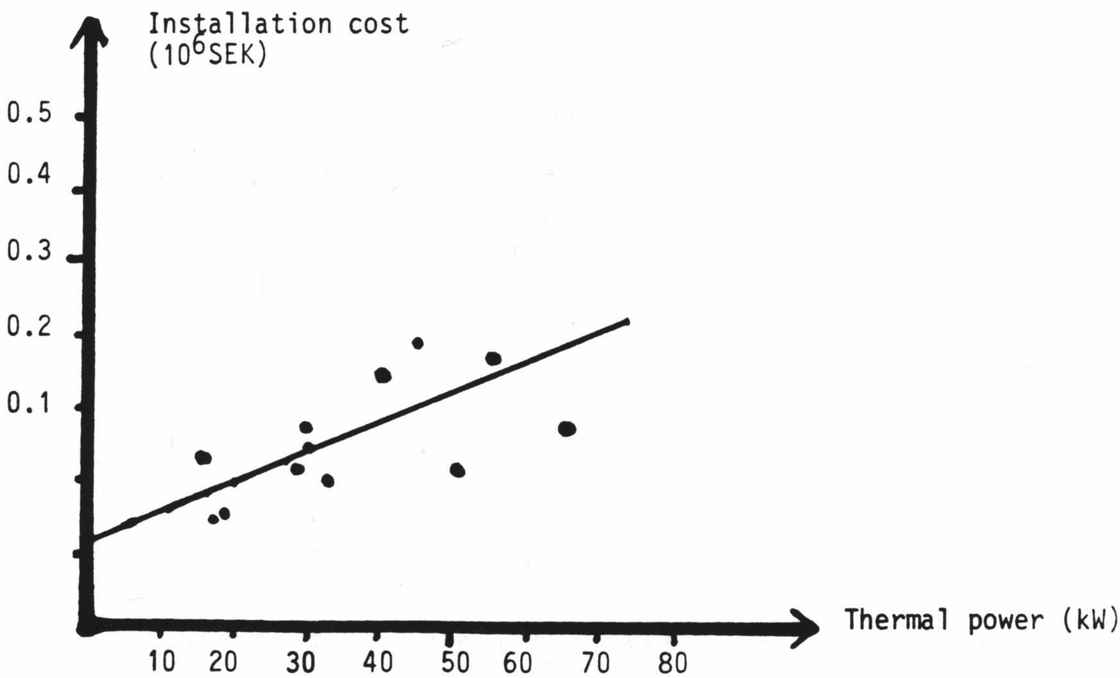

Figure 21. Installation cost for exhaust air heat pumps (49).

An approximate mathematical expression for the line in Figure 21 would be:

$$RC_{EH} = 120\ 000 + 4\ 200 \times P_{EH} \qquad \text{(F33)}$$

Unfortunately, it is also in this report not clear how the costs are calculated, but probably (49 p 26) the buildings are provided with mechanical ventilation systems. In (50) a 17 kW heatpump costs about 40 000 SEK and a 27 kW costs 50 000 SEK, this gives us the following expression:

$$RC_{eH} = 33\ 000 + 1\ 000\ P_{EH} \qquad \text{(F34).}$$

These costs are for the pump alone.

In (51 p 25) a graph is depicted with a cost-power line with the approximate expression:

$$RC_{EH} = 75\ 000 + 4\ 360 \times E \qquad \text{(F35)}$$

This cost concerns the total installation cost except for the accumulator tank.

Looking at the expressions 31 - 35:

$$90\ 000 + 5\ 000\ P_{EH} \qquad \text{(F31)}$$

$$126\ 500 + 570\ P_{EH} \qquad \text{(F32)}$$

$$120\ 000 + 4\ 200\ P_{EH} \qquad \text{(F33)}$$

$$33\ 000 + 1\ 000\ P_{EH} \qquad \text{(F34)}$$

$$75\ 000 + 4\ 360\ P_{EH} \qquad \text{(F35)}$$

It can be found that for the total installations the cost will be approximately:

$$RC_{EH} = 100\ 000 + 4\ 500\ P_{EH} \qquad \text{(F36)}$$

Then has the "power coefficient" in (F32) been excluded and the expression (F34) is only valid for the heat pump device.

However, it is also important to have some knowledge about the life-cycle for the systems. In (48) the write-off time is 10 years, but a lot of the equipment naturally could be used after this time. In my case, where a natural ventilated system is used in the existent house, I have split up the cost function in two parts. One of the parts considers the building measures, e g caulking the pipes, building new pipes to gather the different ventilation pipes together, insulation of the pipes etc. For these kind of measures I have estimated a life-cycle of 30 years. In existent buildings it is often hard to find room for these channels and sometimes they have to be put outside on the roof. In (52 pp 42 and 44) the cost for changing a natural ventilation system to a centralized system with mechanical ventilation is about 9 000 SEK/apartment. Adding a heat pump with necessary extra equipment costs about 14 000 SEK/apartment more.

From the expressions 31 - 35 and the figures above it is obvious that it is very hard to predict the ventilation retrofit cost with a big accuracy. Considering the LCC for the equipment it is also necessary to split the cost in at least two parts. The building measures have a rater long life-cycle, while the machinery has a much shorter time of economic life. Because of this I have assumed that approximately 90 % of the initial cost (100 000 in (F36)) consists of the building measures, while the rest is the actual heatpump machinery cost. This means that the retrofit cost expression will become:

$$RC_{EH} = 90\ 000 + 10\ 000 + 4\ 500 \times P_{EH} \qquad \text{(F37)}$$

In (86 p 27) the investment cost for a 24 apartment multi-family building is approximately 7 000 SEK/apartment for the ventilation equipment and approximately 11 000 SEK/apartment for the heat pump. The total cost was 432 300 SEK and the heat pump power was 16 kW. The expression (F37) for this case thus seems to be too low.

4.1.5.2.3 The ventilation equipment. Ventilation air heat exchanger

Another means to take back the energy from the ventilation air is a heat exchanger. The warm air going out from the building is then heating the cold air going in to it. However, it is very hard to find room in the existent building for the ventilation pipes, that will lead the heated outside air in to the different rooms in the building. In (52 p 44) the cost for a system with a heat exchanger (air to air) is about 27 000 SEK/apartment or about 4 000 SEK more per apartment than the heat pump. No closer specifications have been mentioned in (52) and thus it is hard to discuss the accuracy of the information. In Sweden there have only been a few installations described in the literature with this kind of equipment, unfortunately, with bad experiences. In (53) the efficiency in the system was as low as 15 % and this because of leaking channels etc. Also in (54) and (85) this is mentioned. Using the information above the Retrofit Cost for ventilation air heat exchanger in my case will be about:

$$RC_{EX} = 20 \times 27\ 000 = 540\ 000 \text{ SEK}$$

4.1.5.3 The ventilation system; Energy cost, LCC and optimization

In my case the existent ventilation flow is 3 840 m^3/h. (See above.) If caulking the windows and doors this flow is decreased to 2 400 m^3/h. The number of degree hours in Malmö is 105 241 and, thus, the energy cost during one year will be for my existing house:

$$3\ 840 \times 1.18 \times 1.005 \times 105\ 241 \times 0.30 : 3\ 600 = 39\ 937 \text{ SEK}$$

The present value will be (as earlier during 50 years):

$$18.26 \times 39\ 937 = 729\ 262 \text{ SEK}$$

Caulking the windows will deminute this to 455 788 SEK.

The cost for this retrofit is 22 000 SEK each time the retrofit is needed. I have assumed that the life-cycle for caulking is 10 years and thus the present value will become:

$$22\ 000(1 + 1.05^{-10} + 1.05^{-20} + 1.05^{-30} + 1.05^{-40}) =$$
$$= 52\ 012 \text{ SEK}$$

The LCC for the retrofitted system will thus become:

$$455\ 788 \times 52\ 012 = 507\ 800$$

It is profitable to caulk, because the caulked building has a lower LCC. The optimization process will be similar to that concerning window optimization. Either the retrofit is chosen or else not. The mathematical expressions will be shown at the end of this chapter.

Considering a heat pump retrofit makes the process a little more cumbersome and this because the heat pump takes its heat from the air flow. Decreasing this by caulking the windows means that the heat pump has less heat to use. It might therefore be profitable to install a heat pump and leave the windows leaking air into the building.

The heat pump takes the heat from the exhaust air and lowers its temperature. Usually the temperature difference is 15 ^{o}C, but as told in (46) it is sometimes optimal to make the difference bigger. This requires that the air heat pump can be defrosted. In this thesis 15 ^{o}C temperature fall is assumed. This means that the energy taken from the air is 3 849 x 1.18 x 1.005 x 8 760 x 15 = 598.3 x 10^{6} kJ each year. With the energy cost of 0.30 SEK/kWh, this means that energy is recirculated for 49 864 SEK. However, the heat pump must have energy (in most cases electricity) to work. With a heat factor of 3, which is common for this kind of heat pumps (46 - 51) this will cost:

$$\frac{598.3\times10^{6}\times0.295}{3\ 600\times3} = 16\ 324 \text{ SEK each year}$$

The energy price for electricity has then been assumed to 0.295 SEK/kWh (55). The present value for the recirculated heat is 18.26 x 49 864 = 910 516 SEK. Assuming that the <u>building measures</u> done to the ventilation system costs 90 000 SEK (F37) each time it is retrofitted, the present value will become with an economic life-cycle of 30 years:

$$90\ 000 + 90\ 000 \times 1.05^{-30} - 1/3 \times 90\ 000 \times 1.05^{-50} =$$
$$= 108\ 207 \text{ SEK}$$

The heat pump cost has to be calculated from the need of power, which is:

$$3\ 840 \times 1.18 \times 1.05 \times 15 : 3\ 600 = 18.97 \text{ kW}$$

The cost will therefore be (F37):

$$10\ 000 + 4\ 500 \times 18.97 = 95\ 834 \text{ SEK}$$

Assuming the life-cycle of the pumps is 15 years the present value will become:

$$95\ 384(1 + 1.05^{-15} + 1.05^{-30} + 1.05^{-45} - 2/3 \times 1.05^{-50}) =$$
$$= 157\ 426 \text{ SEK}$$

The existent LCC for the ventilation system is 729 262 SEK. (See above.)

The energy conserved by the heat pump calculated above has a value of 910 516 SEK. The cost for retrofitting is 108 207 + + 157 426 + 18.26 x 16 234 = 562 065 SEK.

The LCC for the ventilation equipment will thus become

729 262 + 562 065 - 910 516 = 380 811 SEK.The heat pump is therefore very profitable.

Caulking the windows makes the flow lower or 2 400 m^3/h. The heat taken out of this flow will be worth 569 072 SEK.

The cost for electricity will now become 186 297 SEK. The heat pump cost will be 10 000 + 4 500 x 11.85 = 63 325 SEK, which present value equals 104 514 SEK.

The costs are:

Electricity	186 297 SEK
Heat pump	104 514 SEK
Building measures	63 325 SEK
Caulking	52 012 SEK
Sum	406 148 SEK

The energy recirculated is worth 569 072 SEK, or the difference is 148 021 SEK. The system with the heat pump, but without caulking, saved more money or 348 450 SEK. The "heat pump-caulking" system thus has to be avoided.

The same considerations have to be done for the heating exchanger equipment. The manufacturers of the air to air exchangers predict an efficiency of about 0.75 for the equipment. This is not often the situation in real installations due to (54 p 50). A more adequate figure is 0.57 for the four tested installations. Using this figure the recirculated heat will be 598.3 x 10^6 x 0.57 = 341.0 x 10^6 kJ each year. This is worth 518 935 SEK during 50 years. The equipment and installation cost is about 540 000 SEK the first time it is installed, so in this case the installation is not profitable. Using the same life-cycle for the heat exchanger as for the building measures, i e 30 years, the retrofit cost will become 649 242 SEK.

Of course, these calculations are very approximate and especially for the retrofit costs the uncertainties are immence. However, as told before, the scope of the thesis is to show that it is possible to calculate an optimal retrofit strategy, not to find the optimal one. Future research has to give better information about the boundary conditions to the model elaborated.

The objective function (F29) is now getting a little tedious to repeat, so this time I will only show the part that has to be augmented.

$$\ldots + Y_{22}(455\ 788 + 52\ 012) + Y_{23} \times 729\ 262 + Y_{24}(729\ 262 + 562\ 064 - 910\ 516) + Y_{25}(729\ 262 + 406\ 148 - 569\ 072) + Y_{26}(729\ 262 + 549\ 242 - 518\ 935) \qquad \text{(F38)}$$

Subject to:

$Y_{22}, Y_{23}, \ldots\ldots, Y_{26} = 1$ or 0 integers

$Y_{22} + Y_{23} + Y_{24} + Y_{25} + Y_{26} = 1$

The solution to this is $Y_{24} = 1$ and $Y_{22} = Y_{23}\ Y_{25} = Y_{26} = 0$.

Of course, there is a possibility that for some combination of prices it could be profitable to combine a heat pump with heat exchanger etc, but for the boundary conditions valid today or plausible tomorrow this will not happen. These theoretical, but very improbable cases are thus excluded from the model. I have now evaluated a model that optimizes a simplified building with a climate shield and a ventilation system. However, the model only considers the energy cost as a constant 0.30 SEK/kWh, which, of course, is incorrect for many cases. The model up to is now only evaluated for the energy consuming parts of the building and I therefore have to add the energy supply system, i e the boiler or other kind of heating system.

4.1.6 The heating system

In order to choose a proper heating system the first thing to