Refurbishment of industrial buildings

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Abstract

When a building is subject for refurbishment there is a golden opportunity to change its behavior as an energy system. This paper shows the importance of careful investigations of the processes, the climate shield and the heating systems already present in the building before measures are implemented in reality. A case study is presented dealing with a carpentry factory. The building is poorly insulated according to standards today, and initially it was assumed that a better thermal shield would be of vital importance in order to reach optimal conditions. Instead, it is shown that the main problem is the ordinary heating system. This uses steam from a wood–chips boiler and the wood–chips come from the manufacturing processes. These wood–chips are therefore a very cheap fuel. The boiler had, during decades of use, slowly degraded into a poor state. Hence, aero–tempers using expensive electricity have been installed to remedy the situation. These use not only expensive kWh, but also very expensive kW due to the electricity tariff. It is shown that electricity for heating purposes must be abandoned and further, that this could be achieved to a surprisingly small cost. By stopping a large waste of steam it was possible to find resources, in the form of unspent money, for further mending on the existing heating system. Not only economy, but also environmental hazards in the form of CO_2 emissions urges us to abandon electricity and instead use heat from cheap bio-mass fired boilers. Such equipment saves environment at the same time as it saves money.

Introduction

After the oil-crises in the 1970-is, Swedish authorities have done tremendous efforts to reduce demand for oil in the Swedish energy system. Special subsidiaries were implemented where building owners were allowed to borrow money for very low interest rates if energy conservation and oil-reducing measures were introduced on their buildings. If inflation is considered even negative interest rates were in practice. In central parts of towns and cities it was also almost mandatory to connect the buildings to the district heating system. In more rural parts, electricity heating was encouraged. Building envelope, and ventilation system retrofits were also popular, such as adding extra insulation on the attic floor or installment of exhaust air heat pumps.

During recent years the greenhouse effect has been put into focus. Certain gases, such as carbon dioxide CO_2, in our atmosphere are very important for our climate but too much of these gases may result in an increase of the average temperature of the earth, which in turn might lead to disastrous effects because of increased desert areas and a rising sea level. Sweden, as well as many other industrial countries, has therefore decided to reduce, or at least not to increase, its CO_2 emissions into the surroundings. Because of the successful reduction of our dependence of oil, and low electricity prices, electricity is now in use for purposes such as space heating, drying, hot water heating et c.

The electricity market in Sweden was until a few years ago regulated and the end user could only buy this form of energy from one supplier. This is not so any more, and nowadays a number of companies offer electricity even to household consumers. Because of the increased competition, electricity prices started to decrease from already low levels. This, however, lead to unpredicted effects. Profits for the electricity suppliers fell and no one wanted to run high running–cost generators such as gas turbines or oil–fueled condensing plants. During cold winter days such facilities are necessary or else electricity must be imported from countries such as Germany and Denmark. Such imported electricity is on the margin based on fossil fuel generation because there is always such electricity generation present. Even if Sweden only to a small amount have its own such power stations, a saved or conserved kWh will lead to lower emissions of CO_2. This is so even if the actual reduction is achieved abroad.

Also the European Community, EC, has started to deregulate the inner market of electricity and for industrial end users the new rules are supposed to be valid at this very moment. Thus, it is possible to buy and sell electricity on a very large scale and prices will probably become of the same magnitude throughout the EC, at least in the long run. Electricity is therefore likely to become more expensive for Swedish consumers.

The case study

Bringholtz Furniture Ltd. is sited in a small village called Ruda about 300 km south of Stockholm. The company manufactures high grade furniture in massive wood. The Swedish designer Carl Malmsten is represented with several products. Established 1926, the factory has been rebuilt and augmented a number of times. New equipment has been implemented, such as modern routers and other machinery. Parts of the old factory are, however, still the same as before. All machines are today, of course, operating by use of electricity but there is also an old steam system where wood residuals are burnt in a boiler. These residuals are a very good fuel because most of them have been dried to a low moisture content and also because the wood species e.g. beech and birch used in the factory have high heating values.

We applied the following strategy for dealing with this energy system:

1. We examined how much energy that was actually used in the factory both in the form of electricity and heat. We used historical data from the electricity supplier and made our own measurements on the boiler for this examination.

2. We tried to find out how much energy that should be used if all things and equipment would have worked as expected. This was achieved by

calculations on the climate shield, ventilation equipment and the domestic hot water heater.

3. We calculated a cost for that energy. There are two different heating systems, one operated on electricity and one on wood-chips. Electricity is about five times more expensive than wood-chips so this was a crucial question to address.

4. The cost for different energy conservation measures competes with cost for supplying the heat. This struggle was elucidated by use of special computer software for retrofit optimisation. The best solution was found when the life cycle cost for the building was as low as possible.

The use and cost for electricity

In Sweden there is now a de-regulated market for electricity. In this system one company, the electricity grid owner ”Sydkraft Nät AB in our case”, only supplies the grid. On the other hand they have a monopoly and because of this no other company is allowed to offer the same service. Another company, the energy supplier, must provide the factory with the actual kWh, in our case i.e. ”Sydkraft Försäljning AB”. Both companies are today part of the European company ”EoN”, sited in Germany. The factory owner can, however, buy electricity from a number of other suppliers as well, so EoN is not the only possible company to make business with, i. e. for the actual kilowatthours. The first company is responsible for monitoring the electricity consumption. It does so by measuring the number of kWh used during one hour. These values are stored in a memory located in the electricity meter which can be assessed from the Sydkraft computers. The values are after this analysed and used as a basis for the electricity bill. The bill is based on the tariffs used by the two companies. There is, of course a cost for the kWh used, but also costs that are based on the demand in kW. Below these costs are studied in close detail just for finding ways to make them lower. The procedure with monitoring, and collecting, values by computers, makes it possible also for the carpentry factory to analyse its electricity demand load pattern. Just by making a phone call, the factory can achieve figures of their electricity use, hour by hour, for e.g. one full year. In Figure 1 we have used these values for drawing a so called duration graph where the values are sorted in decending order.

The maximum electricity consumption during one hour was monitored by the electricity meter to 138 kWh, and hence, the demand was 138 kW. It is also interesting to study when these peak values occur and in Table 1 the 30 largest values are shown.

The highest demand was actually registered on two separate occasions, April 23 at 10 a.m. and November 14 at 12. In reality, demand could have been much higher during e.g. the first five minutes of the hour but if that was the case it must have been lower than 138 kW elsewhere. It is also found, see Figure 1 that there is a clear peak, say above 120 kW, containing a limited number of kWh. There is also a basic load of the magnitude 20 kW.

Normal practice for Swedish companies is to use a so called demand tariff. By use of a small computer program written in C it was possible to study exactly how much money the company had to pay for the electricity, see Table 2.

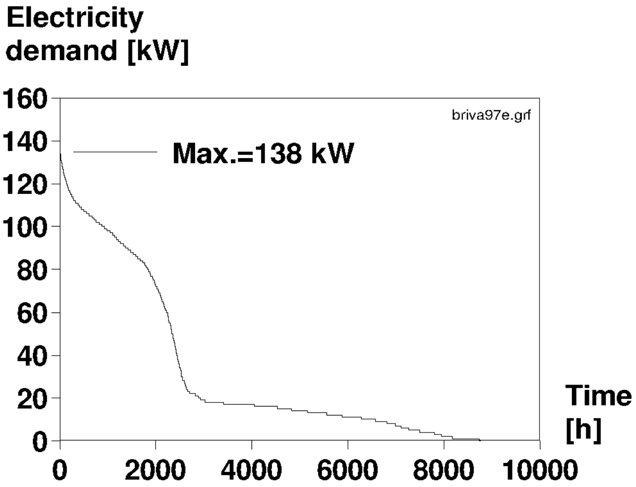

Figure 1: Duration graph for the electricity use in Bringholtz Furniture Ltd.

Date	Time	Energy	Date	Time	Energy	Date	Time	Energy
Apr 23	10	138	May 30	8	134	Oct 27	9	133
Nov 14	12	138	Oct 27	8	134	Nov 04	15	133
Jun 03	7	137	Nov 17	8	134	Dec 08	9	133
Nov 11	9	137	Dec 01	15	134	Dec 12	14	133
Feb 03	12	135	Dec 08	8	134	Feb 17	8	132
Feb 03	13	135	Dec 16	12	134	Oct 24	11	132
Nov 05	8	135	Feb 27	9	133	Oct 27	12	132
Nov 05	9	135	Mar 26	13	133	Oct 30	9	132
Dec 16	13	135	Apr 23	11	133	Nov 20	13	132
Feb 03	11	134	Apr 28	14	133	Feb 03	15	131

Table 1: Peak load details of the electricity useage at Bringholtz.

Some comments might be necessary. The energy cost is based on several tariff elements. The cost paid to the grid owner is 0.052 SEK/kWh during winter working days and 0.028 at other times. The energy supplier charges 0.309, 0.247 and 0.184 for winter working days, winter nights as well as spring and autumn working days, and other times. The actual price for each kWh was therefore about 0.35 SEK in the high cost segment. (1 Euro ≈ 9 SEK.) The demand cost is based on the average of the two highest registred demands for different winter months, and P_{av} equalled about 136.5 kW. The demand cost is normally based on the subscription level but only if the subscription is not trespassed. The company had a subscription level of 150 kW. Only 138 was used but if the company had used more than 150 kW the cost for each kW will become twice those for ordinary kW, i.e. 908 instead of 454 SEK/kW. Too low a level is therefore a bad solution if there is no load management equipment installed in the factory. Further, if the level is passed this new value will be valid. Note also that it is more expensive to pass the subscription during the winter. It is obvious that the actual cost for the kWh is only a part, ≈ 40 %, of the total cost. In Table 1 it is shown that the peak is 138 kW. This high value occured two times

Type of cost	SEK
Energy cost	82,398
Demand cost, 137 × P_{av}	18,700
Subscription cost, winter, 420 × P	63,000
Subscription cost, year, 37× P_{sub}	5,550
Reactive power demand cost, 205 ×P_r	6,765
Summa summarum	184,413

Table 2: Cost elements [SEK] in the demand tariff for Bringholtz Furniture Ltd.

during the examined year. The first time was April 23. This peak is outside of the winter season, which falls between November to March, and hence it is not of the same importance as the second peak, occuring November 14. December 16, 1 p.m., another peak occured. The average of these two values, 136.5 equals the P_{av} in Table 2. If peaks in the winter can be avoided, such actions save more money than the same action during summer and spring. In theory, each measure that saves one kWh, which at the same time results in a reduction of the peak with 1 kW, might have a value of 454 SEK. However, things are not so nice in reality. A closer look at the input data file for Figure 1 shows that the level 120 kW, which is used as an example, is passed 139 of the 8,760 hours during one full year. If the company could decrease the subscription level to 120 kW about 14 kSEK each year could be saved. This can be acieved by saving 984 kWh and each of these kWh will therefore have a monetary value of about 14 SEK. ”Normal” kWh have only a value of 0.3 SEK so peak load kWh have much higher economic significance than other kWh. Hence, profitable energy conservation is best achieved if it is applied on the most expensive kilowatthours. Such load management measures have been described in [1] but here we add even more such possibilities. Noteworthy from 1 is that load management might have been difficult on February 3, November 5 and December 16. These dates are present several times in the table. If peak load shaving was started at 11 February 3, it must continue for three consecutive hours because peaks were also present at hours number 12 and 13, otherwise the peak might have been larger than it was originally. It should be mentioned that the structure of the tariff is today, May 2005, somewhat different but the level of the tariff is about the same. In order to save expensive energy, and not only energy, we must examine available options in the factory and the first one is to use the wood–chips fired boiler.

The wood-fuelled steam heating system

A carpentry factory does not only produce furniture, a lot of wood residuals, such as wood-chips, sawdust and other items are manufactured as well. Instead of putting this waste on the scrap yard it can be utilized as fuel in a wood–chips fuelled boiler. The steam system of the factory cannot be covered in full detail in this paper but the principal function of the system is shown in Figure 2. More details on steam heating systems can be found in [2] pp. 164.

The wood residuals are put into the boiler where steam is produced. Because of the higher pressure of the steam, compared to the atmosphere, the steam is

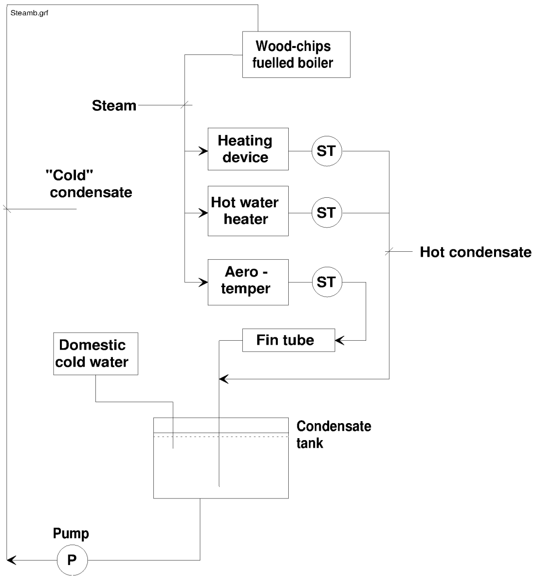

Figure 2: Principal view of the steam heating system

transferred inside the steam pipes out to e.g. an aero-temper. In this apparatus the steam is supposed to condensate into water, and at the same time leave its latent heat of vaporization. The water passes a so called steam trap, ”ST” in Figure 2, and flows by use of gravitation down to a tank. This tank is not under pressure and to ascertain this, a pipe is led outdoors. The still warm water is after this pumped into the boiler and new steam is produced. Note that the pump must be able to overcome the preasure in the steam system. After a steam trap, only water should be present in the pipe. This newly condensed water is, however, very warm and this is why it is sometimes led through a finned tube for providing further heat to the premises. The main problem with all such steam systems is that many times the steam traps, not only are open for water and air but for steam as well. Hence, steam is led down into the tank and, in turn, outdoors. Leaking steam traps are therefore the reason for tremendous waste of energy, and money. This problem was also present in the Bringholtz factory, see Figure 3, showing the temperature on the outside of the condensate pipe just before the tank in Figure 2

The horisontal scale shows the number of minutes passed since midnight. During the night the boiler was turned off and, hence, the temperature on the outside of the steam pipe slowly declined. At about 06.30, i.e. after about 400 minutes, wood–chips were put into the boiler and steam was produced. Now, the temperature increases very fast and it is many times even above 100 °C which shows that steam must pass through the pipe. This because of athmospheric pressure in the tank when liquid water cannot have a higher temperature than 100 °C. After 10 hours the fire in the boiler is extinguished and the pipe starts to get cold again.

Because of all steam flowing down into the tank, the water becomes very hot and arriving steam cannot fully condensate. Hot steam is therefore led outdoors to no use at all. This is shown in Figure 4 where the temperatures on the pipes

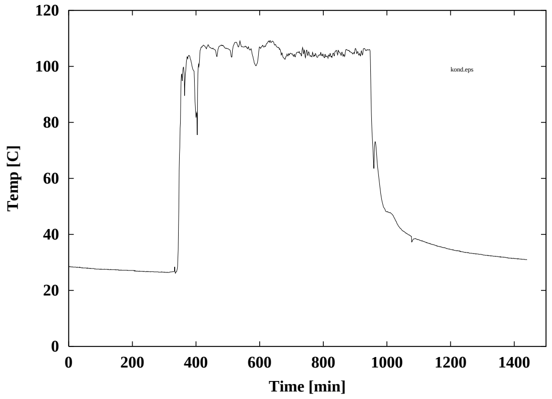

Figure 3: Surface temperature on the pipe for returning condensate.

leading steam from the boiler and water into the boiler are presented.

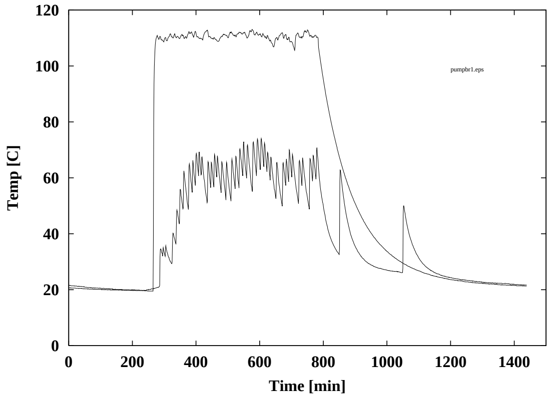

Figure 4: Temperatures on the surfaces of the steam and water pipes from and to the boiler.

The temperature on the condensate pipe fluctuates according to when the pump is used. When the pump operates the temperature rises or is constant while it goes down when the pump is idle. It is clear that the pump is turned on and off a significant number of times each day. The pump is turned on when the water level in the boiler is too low and turned off when the level is high enough. It is also obvious that the water level in the boiler goes down even if the boiler is turned off, this because the temperature on the pipe increased very fast, e.g. after 1,000 minutes. This indicates a leaking valve. Our first measure was, however, to find a cheap way to stop the unrestricted steam flow through the system. A new steam trap, a FT 14 from Spirax/Sarco was used. This is equipped with a floating body which opens a valve when water is present. When the water has been drained the valve is closed until "new" water is present in the trap. This type was chosen because of its "fool-proof" construction. The new trap was installed just before the point where the condensate was led into the tank. Figure 5 shows the new behavior, cf. with Figure 4.

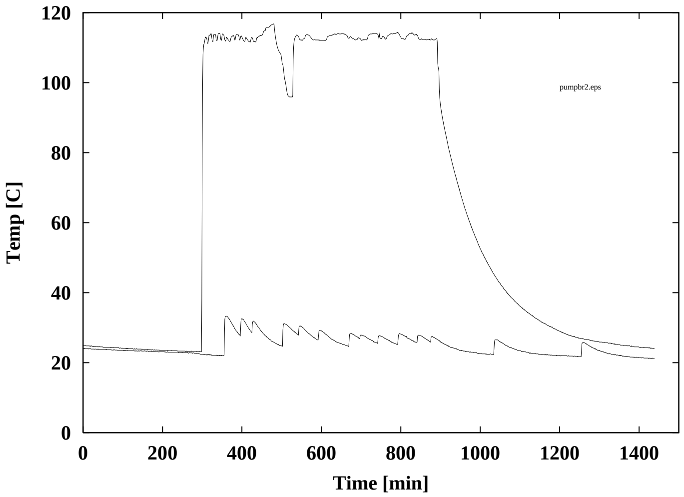

Figure 5: Temperatures on steam and water pipes with new steam trap.

By this measure one "chunk" of water pumped into the boiler lasted about 50 instead of 6–9 minutes. Also the temperature of the condensate became significantly lower, about 30 instead of 60 °C. It is therefore shown that at least 80 % of the steam was wasted and only 20 % was used for useful heating. We have also installed a "water-metering" device between the tank and the boiler. The meter delivers one pulse for each 2.5 litres of water passing through the pipe. In Table 3 registrations from one hour is shown.

Time	Pulses	Litres	Time	Pulses	Litres	Time	Pulses	Litres
06.05	10	25	6.25	2	5	6.45	2	5
06.06	11	27.5	6.26	11	27.5	6.49	2	5
06.11	5	12.5	6.27	9	22.5	6.50	10	25
06.12	12	30	6.33	8	20	6.51	10	25
06.13	1	2.5	6.34	12	30	6.57	8	20
06.19	8	20	6.43	9	22.5	6.58	12	30
06.20	10	25	6.44	10	25	6.59	2	5

Table 3: Registrations from the water meter, from 6.01 to 7.00, 2004-03-12

During one "pumping–batch" about 21 such pulses were registred equalling 52.5 litres of water, see Table 3 at 06.05 and 06.06. The latent heat hidden in one litre of water transferred to steam is 2,257 kJ/kg, [3] p. 846, or 0.627 kWh, and one pumping session therefore equals 33 kWh. It should be noted that even more heat is present in the steam/water, i.e. the sensible heat. This amount adds up to 4.18 kJ/kg°C, [3] p. 846, or $\approx$ 6 kWh in one chunk of water. In total the wood–chips boiler therefore produces about 40 kWh every time the pump starts. This happens each 6–10 minutes and implies that the boiler works at 240 to 400 kW when it is operating. It is now possible to calculate the used amount of wood–chips heat in the factory. Assume that the boiler in average operates at 320 kW. It is in use about 10 hours each working day and hence

3,200 kWh is produced. Each month has about 20 working days so 64,000 kWh is actually transferred through the premises during about 8 months each year. This adds up to 512 MWh. This figure must now be compared to the amount that should have been be used according to the climate and the insulation standard of the building. First, however, some notes on energy conservation measures on buildings.

Optimal refurbishment of buildings

When a building is designed and built, the standard of the building envelope, heating equipment and other facilities are set to what is common practice at this time. After a number of years the building becomes delapidated and sooner or later something must be done. One solution is to demolish the building, and build a new one, but it is also possible to change the existing building by renovation. The question is then: How should a building be retrofitted in the best way?

The first thing to answer is what the word ”best” means. We therefore need a concept where we can compare two, or several, solutions and evaluate which of all these, that actually is the best. Fortunately, such a concept exists and it is called the Life-Cycle Cost, abbreviated, LCC. The LCC contains all cost that a proprietor must pay during the total life of a building. These costs do not emerge at the same time but instead several years might pass before certain measures must be done a second or third time. Other measures must be paid for several times a year. Due to economic theory a cost in the future is better than the same cost now. This fact is dealt with by use of so called present value, PV, calculations where an interest rate is used to transfer future costs to present time. For a measure, e.g. changing windows in poor condition to new ones, this present value is calculated as:

$$PV_1 = C_o(1+r)^{-m} \tag{1}$$

where C_o equals the actual cost when it occurs, r is the interest rate, and m is the number of years before the cost emerges. Some of the costs paid by the bulding owner emerge every year, one example is energy costs. These must also be calculated in the form of a present value and this is done by use of the following expression:

$$PV_2 = C_a \frac{(1+r)^{-n}}{r} \tag{2}$$

where C_a is the annually recurring cost, and n is the number of years estimated for the life cycle. (Below it is shown how these expressions have been used for optimization of the Bringholtz factory.) The knowledge on how to calculate the LCC has been around for quite a time, see [4] for an example, but the method had some drawbacks which reduced its popularity. Such drawbacks are e.g. to predict which interest rate to use or what future costs of energy will be. In the LCC all costs that are connected with the refurbishment, and future use, of a building are added. A building with a low LCC is therefore better than a building with a higher such cost. Sometimes a combination of retrofit measures can result in a low LCC and in such a case this is better than to leave the building as it is. A solution with the lowest possible LCC is of course the very best and then we have an optimal solution. Unfortunately, it is a cumbersome process to calculate the LCC, and even harder to find the lowest possible of all such costs. At the time when [4] was written such calculations could not be utilized everywhere because of lacking number–crunching capacity. With the introduction of personal computers things changed. The LCC calculations could now be dealt with e.g. by use of computer programming in Fortran. It was therefore possible to calculate the LCC for a large number of different solutions, and after this pick the one with the lowest value. Such a solution was used in early versions of the so called ”Opera–model”, see [5] for an example. It is not possible to dwelwe very deep into the inner algorithms of Opera but Figure 6 at least gives a hint on what happens.

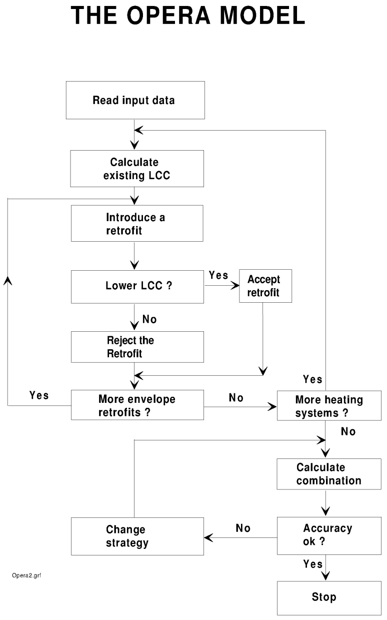

Figure 6: Schematic view of the Opera model.

A building in the form of input data is stored in a data file. This data file can be changed by using a graphical user interface. In Opera this is nowadays a Windows API application written in the programming language C. When the program starts the first thing that happens is the calculation of the LCC for the existing building. So far, nothing else than so called inevitable measures are applied. If it is necessary to install a new boiler after five years, this is done. Bad windows are changed to new ones if they have to be changed and so on. It is also necessary to buy fuel for the heating system et c. All these costs are added, by use of present value calculations, and this sum shows the LCC for the existing building.

The next step is to introduce a retrofit, e.g. changing the existing two–glazed windows into new three–glazed ditto. This measure saves some money because of lower energy bills. Unfortunately, it also costs money because of the cost for new windows and. There are also costs for demolishing the old ones which perhaps could be used a number of years before they had to be changed. A new LCC is now calculated and compared to the one for the existing building. If this new LCC is lower, then the retrofit is supposed to be profitable, and chosen by the program as a candidate for includement in the optimal solution. Now a new retrofit is tested, e.g. adding extra insulation on the attic floor.

When all such measures, which affect the climate shield, or demand for heating, the program changes the heating system in the building. Instead of an oil–fired boiler a district heating system is tested. The process starts all over again and a climate shield retrofit is tested if profitable. With this new heating system other canditates are chosen and the heating system is once again changed. Eventually, we have a number of heating systems with different sets of possible canditates for affecting the demand in the building. The program now chooses the set which is cheapest, i.e. the one with the lowest LCC.

Unfortunately, one retrofit measure may affect the possible savings of another. This is essential to consider, especially dealing with industries where a lot of the demand for space heating comes from waste heat from processes, such as dryers, gluing equipment and so forth. Consider e.g. a foundry where excess heat from the process partly covers space heating demand. This makes the heating season short. If for instance the attic floor is extra insulated, the heating season becomes even shorter, and perhaps no heating is necessary at all. If now extra insulation is put on the walls as well, no heat is saved at all but extra ventilation is needed because the temperature in the premesis will become too high. This example shows that it is necessary to study the resulting LCC for the combination of proposed candidates. For normal conditions, a heating system with low operating costs is likely to be chosen which in turn implies that only a few climate shield retrofits are profitable. The LCC for the combination will therefore almost always be approximately the same as the expected LCC, and hence the optimal solution is found without extra work with the model. One important fact to note is that the model, and the optimisation, deals only with the cost for the system. All measures, and their consequences, must therefore be translated to costs expressed in money. First, however, we need to find how much heat that is actually needed in the factory.

Calculation of the energy demand

The carpentry factory was established 1926. Some parts of the factory are of that age but other parts are newer. The older parts are nowadays used mostly as a storage for products and, hence, the temperature in those parts are set to a lower value than in the parts where people work more frequently. One part of the newer building is used for kiln dryers and waste heat from that process makes temperature high. Different parts of the building have different types of walls and because of this the heat transferred through the walls differs according to the wall considered. Even if the Bringholtz factory is rather small it is necessary to make ”clever assumptions” on the buildings status as a whole. The newer parts of the building are manufactured by use of large building elements in so called autoclaved aerated concrete, i.e. Ytong or Siporex, with a thickness of about 300 mm. Such a construction results in a U-value of about 0.5 W/m^2K if no extra insulation is applied. Nowadays, such high a U–value is not applicable but the standard of this part of building was set 1962. The floor is manufactured of ordinary concrete but it is not in contact with the outdoor air so here it is assumed that an applicable U-value is 0.3 W/m^{2}K.

In order to implement the building in the Opera computer program we have calculated the floor, and roof, areas to 3,000 m^2, the wall area to 1,200 m^2. There are 12 windows of the size 6 m^2 oriented to the west, 7 of 2.3 m^2 to the east, 1 of 8 m^2 to the south and 1 of the size 3.8 m^2 to the north. All windows are of the double-glazed type with a U-value of 3.5 W/m^{2}K. These facts result in a total so called UA-value of 3,350 W/°C, see Table 4.

Building part	U-value	Area	U×A
Attic floor	0.5	3,000	1,500
Floor	0.3	3,000	900
Walls	0.5	1,200	600
Windows, north	3.5	3.8	13.3
East	3.5	16.1	56.4
South	3.5	8	28.0
West	3.5	72	252.0
Summa summarum	-	-	3,350

Table 4: Calculation of the so called UA-value in W/K.

All carpentry factories have a system for wood residuals transport. Sawdust, wood-chips and other fractions of the processes are transported to the bin for wood-fuel using a fastly flowing air stream inside special ducts, or pipes. This air stream is produced by means of a fan operated by a motor, which in turn, is run on electricity. The speed of the flow must be of the magnitude 25 m/s, or else the chips will sediment inside the pipes which leads to congestion, and choke. We have monitored the air speed by an ordinary Pitot tube, see e.g. [6] p. 92, and found it to be about 16 m/s, i.e. less than expected but the system seemed to work properly in spite of that. There are four such systems serving different machinery in the factory but it is not necessary to use all four systems at the same time. Most machines were coupled to a large tube with a diameter of 0.5 m and hence about 11,000 m^3 of warm in–door air is led out to the surroundings. The other three systems return some of the warm air to the premises. Unfortunately, it was very difficult to actually monitor the flow of this returning air because of large ducts and a slow air speed. However, our judgement is that about 19,000 m^3 of warm air is wasted each working–hour. Sometimes the flow can be significantly higher but on other occasions it is approximately 50% of that amount.

The Opera model is supposed to be used for residences where ventilation is used 24 hours a day. This is not the fact in an industry. Here, it is therefore assumed that the ventilation rate is reduced to 23 % or 4,300 m^3 each hour because only about 23 % of the hours during a month are working–hours. The volume of the building is 11,500 m^3 and, hence the ventilation changes the indoor air about 0.4 times each hour. The heat stored in this air is calculated as:

$$Q = c_p \rho v \frac{1,000}{3,600} \tag{3}$$

where c_p is the heat capacity for air, ρ is the density of air, v is the air flow each hour, while the rest is for changing the Joules to kWh. The expression becomes, see [7], page 646:

$$Q = 1.0057 \times 1.1774 \times 4,300 \times 1000 \div 3,600 = 1,414$$

Due to some further approximations necessary for the computer program the value actually used was 1,465 W/K.

The factory is, as mentioned above, located in a small village called Ruda which in turn is sited close to Kalmar, Sweden. Kalmar can be found in available meteorological statistics and the average monthly temperatures are shown in Table 5.

Month	Temp.	Month	Temp.
January	-1.7	July	17.2
February	-1.9	August	16.3
March	0.0	September	12.3
April	5.1	October	7.6
May	9.8	November	3.6
June	14.5	December	0.9

Table 5: Average mean of monthly temperatures in °C for Kalmar, Sweden.

The indoor temperature in the factory differs depending of the time of day, season etc. In order not to underestimate the demand for space heating this value is assumed to be 22 °C. In January there is 744 hours so the number of degree–hours, DH, is calculated to:

$$DH = 744 \times (22 - -1.7) = 17,633$$

degree–hours for January. There is also a heater for domestic hot water. This device can be run on electricity or the water can be heated with steam. We do not know the consumption of hot water but we have monitored the use of electricity in the heater. On a working–day when the steam system has been turned off, approximately 6 kW were used in the heater. The heater, however was not connected all the time and, hence, it is assumed that 2 MWh was used each month.

The demand for electricity during one full year is approximately 300 MWh. Assuming that about 75 % of this energy is tranferred to heat inside the premesis free heat from appliencies is set to 18 MWh each month. All these facts have now been put into the Opera program and the program starts by showing the demand for heat from the boiler, see Table 6.

Above it was shown that 17,633 degree–hours is present in January. Multiplying this value with the sum of the UA–value, 3,350 and the value for ventilation, 1,465 yields the number of kWh which must be used for balancing the climate. The result is 84,899 kWh but some of this heat is provided by free heat from appliances, i.e. 18,000 kWh, and solar insulation, i.e. 982 kWh. However, 2,000 kWh must be added for heating of domestic hot water, which demand cannot be provided by ”free” heat. The resulting demand provided by the boiler must therefore be 67,917 kWh. During the summer it is obvious that no space

Month	Deg. h.	Heating d.	Hot water	Free heat	Solar	Fr. boiler
1	17632.8	84899.3	2000	18000	982.2	67917.1
2	16060.8	77330.3	2000	18000	1966.6	59363.7
3	16368	78809.5	2000	18000	4347.9	58461.6
4	12168	58587.1	2000	18000	6171.4	36415.7
5	9076.8	43703.4	2000	18000	8545.6	19157.8
6	5400	26000.2	2000	18000	8822.6	2000
7	3571.2	17194.8	2000	18000	8667.1	2000
8	4240.8	20418.8	2000	18000	7391.3	2000
9	6984	33626.9	2000	18000	5401.8	12225.1
10	10713.6	51584.4	2000	18000	3037.2	32547.1
11	13248	63787.1	2000	18000	1230.8	46556.3
12	15698.4	75585.4	2000	18000	653.7	58931.8

Table 6: Heating demand calculations in kWh for the Bringholtz factory

heating is necessary, only domestic hot water must be produced. The demand for one full year adds up to 398 MWh which now must be compared to the measured production in the wood–chips fired boiler which was 512 kWh. Therefore, if these calculations correspond to reality more than 100 MWh is produced in vain. It must also be noted that it is not necessary to ascertain an indoor temperature of 22 °C during nights, weekends and other non–production periods. The calculated demand is therefore too high which aggravates the situation. The next thing to study is the monetary value of this energy.

Energy cost in a dual-fuel system

The Opera–model deals with a number of retrofits, such as adding attic floor insulation or changing windows. All such retrofits are profitable only if they reduce the demand of heat, and by this the demand for money in order to buy energy. An important thing to examine is therefore the cost for this energy, in our case the wood–chips incinerated in the boiler, and the cost for electricity in some aero–tempers and radiators, run on electricity. Because of the possibility to use both heat from the steam system as well as electricity in resistance heaters we here have a dual-fuel system. Fire–insurance regulations prohibit the use of the boiler when no human beeings are present on the premises and therefore it is necessary to use electric heating during, at least some, nights and weekends. We must therefore study not only the costs for the different energy sources but also how much of these that is actually used.

Wood-chips energy cost

Mentioned above is the fact that this fuel one step earlier in the process is considered as waste. It is, nonetheless, important to find out how much heat that can be produced from this waste because when it is in the boiler it is a valuable resource. In [8] p. 150 it is found that the so called heat value of oven–dry wood is about 4,500 kcal/kg, i.e. 5.23 kWh/kg. If wood contains some moisture this calorific value decreases and for a moisture content of 10 %

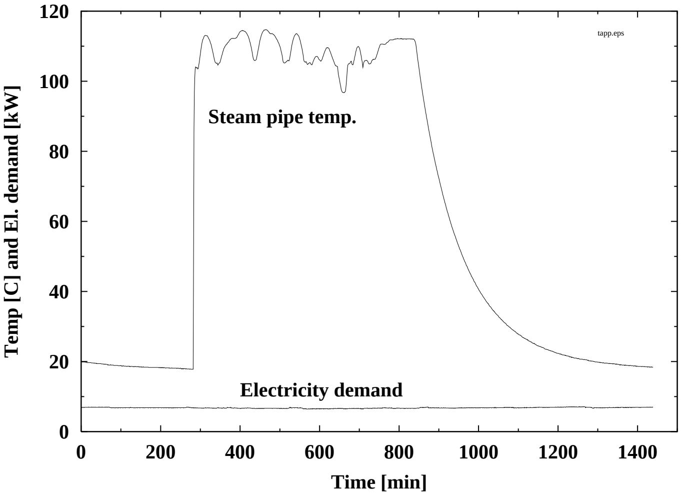

Figure 7: Electricity demand in the domestic hot water heater and temperature on the main steam pipe.

it is reduced to 4.65 kWh/kg. Note that most of the residuals emanate from kiln dried wood so it is rather dry.

Unfortunately, there are not enough residuals from the manufacturing. The company must buy about 500 m^3 on the market to a price of 65 SEK/m^3. The density of wood–chips is about 150 kg for each m^3 so each m^3 corresponds to about 700 kWh. The cost for each kWh is therefore about 0.1 SEK/kWh or if the efficiency of the boiler is considered, about 0.12 SEK/kWh. It is interesting to note that the company buys about 350 MWh wood-chips each year while there were a demand for 365 MWh from the boiler, *vide supra*. The company must produce a lot more than 15 MWh wood–chips each year so it is evident that something is not working as it should. There is not, however, only the cost for the wood–chips. One of the employees must take care of all maintenance and operation of the boiler. This cost has been estimated to 60 kSEK each year. This will certainly make the use of the boiler less profitable but the cost is only to a part dependent on the produced number of kWh.

Heating devices operating by use of electricity

The company has a number of devices where electricity is transferred into heat. For example there is the domestic hot water heater and we have studied how it works by use of an electricity meter, see Figure 7, which shows a day in November 2002. The domestic hot water heater can be operated both on electricity and by using steam. When the temperature on the steam pipe reach a high level, e.g. over 100 °C the electricity demand should be zero, i.e. the electric heating should be turned off. Figure 7 does not show such a behaviour. The demand was about 7 kW all day through. There are also space heating devices run on electricity. These, however, were only of the sizes 2–3 kW and the seemed to operate as they should. The company also have som aero–tempers of the size 10 kW but they were seldomly used. The investigation above shows, therefore, that the space heating demand to a large degree is covered by the steam system and the cost for each kWh must therefore be of the magnitude 0.12 SEK/kWh. This value must be put into the Opera model as important input data.

Calculation of the Life–Cycle Cost

Now it is time for actually calculating the LCC and we must therefore use the two Equations, 1 and 2 extensively.

Retrofits in the form of extra insulation

Consider first the attic floor. In Table 4 it is shown that this building part has an area of 3,000 m^2. Initially, we must find out the shape of the attic floor. If it is in a poor shape we must start with refurbishment immediately but if it is in proper shape this can wait for a long time. In our case no renovation is necessary so there is no need for such an inevitable measure. If, on the other hand, extra insulation is to be added to the attic floor a number of costs emerge. In this study these costs are put in three groups. One, C_1, shows the costs that do not have direct implications on the thickness of extra insulation. In this group costs for scaffolding, demolition et c. are located. In the second group, C_2, all costs that emerge as soon as extra insulation is applied on the attic, but are independent of thickness. In the third group, C_3, all costs that are directly dependent on the amount of insulation are included. The total cost can therefore be presented as:

$$C_{attic} = C_1 + C_2 + C_3 \times t \tag{4}$$

where t equals the thickness of extra insulation. Note that we do not know yet if extra insulation is of interest or not. For a start we must therefore examine the LCC for the building as it is. No energy saving measures are therefore considered in these initial calculations, see the second box from the top in Figure 6. Note that the C_1 value emerges every time when the building is retrofitted for other reasons than for energy conservation. One further such case is when the facade of the building must be changed. If the facade is in a perfect shape it has a high economic value, and hence it is expensive to demolish and rebuild it when you want to implement extra insulation. If on the other hand the facade is in a poor state you must renovate the facade even if you do not aim to add extra insulation. The present value of this so called inevitable cost, calculated by use of formula 1, is therefore of outmost importance. It tells us that it is unprofitable to implement energy conservation measures on good buildings but profitable to do so on poor buildings even if the buildings have identical thermal signatures.

When extra insulation is added on e.g. the attic floor the value of $\sum UA$ will change and get lower. If the original attic floor has the U-value U_{exi}, the added insulation has the thermal conduction k, and the thickness of extra insulation is t, the new U-value becomes, see [9]:

$$U_{new} = \frac{U_{exi}k}{k + U_{exi}t} \tag{5}$$

For mineral wool the value of k equals 0.04 W/m^2K while U_{exi} is found in Table 4.

When t grows larger the demand, and cost, for energy will decrease but at the same time the the cost for insulation, see Equation 4 will increase. At a certain point the total cost is the smallest possible, i.e. optimal conditions prevail, see Figure 8.

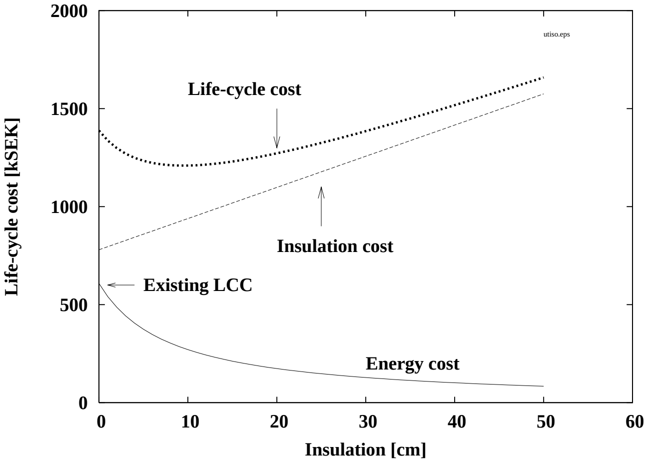

Figure 8: Insulation optimisation of the attic floor

In Figure 8 the insulation cost has been calculated from Equation 4 multiplied with the attic floor area, 3,000 m^2. C_1, C_2 and C_3 have been set to 0, 260 and 530 respectively. The energy cost has been calculated by use of 5 multiplied by the attic floor area, the number of hours for one full year, 8,760, the temperature difference between the indoor temperature, 22 ° C, the average mean outdoor temperature, 7 °C, the cost for heat from the wood–chips fired boiler, 0.12 SEK/kWh. The annual cost has after this been used in Equation 2 with n equalling 50 and r=0.03. In Figure 8 it is found that the optimal level of insulation is about 10 cm, but this is true only if extra insulation is applied at all. The very best solution is to leave the attic as it is today, see the existing LCC which has a value of $\approx$ 500 kSEK, and compare with the LCC if insulation is applied, which is of the magnitude 1,200 kSEK. The high cost for insulation cannot compete with the very low heating cost. In OPERA the optimal level is found by using traditional calculus, i.e. derivating a continous function and setting the value of this to zero.

Retrofits on windows

A similar procedure is undertaken for windows but now you cannot find a continuous function. Conditions are too complex because of different types of glass, number of panes, air gaps, low emissivity coatings and so forth. Instead, different alternatives must be tested. By examining different price lists for windows we found that a normal double–paned window, such as those that are present today, had a cost of about 1,100 SEK/m^2 while a triple-glazed ditto had a cost of 1,300 SEK/m^2. In Table 4 the window areas and their U-values can be found and it is assumed that a new triple–glazed window has a U–value of 2.0 W/m^{2}K. The windows in the factory are in a relatively poor condition and we judged that they have to be replaced by new ones within 5 years. Consider for example the 12 windows oriented to the west. Each window has an area of 6 m^2. A double–paned window therefore costs 6,600 SEK while the triple–type costs 7,800 SEK. It is further assumed that new windows have a life span of 30 years. We now use Equation 1 in order to calculate the existing LCC where the present windows are changed into similar double–paned windows. We get:

$$6,600 \times ((1+0.03)^{-5} + (1+0.03)^{-35} - \frac{15}{30}(1+0.03)^{-50} = 7,286$$

Note that the salvage values have been subtracted from the LCCs. If triple–paned windows are implemented now, we get:

$$7,800 \times ((1+0.03)^{-0} + (1+0.03)^{-30} - \frac{10}{30}(1+0.03)^{-50} = 10,420$$

The difference in cost is 3,134 SEK. With the same input data as for the insulation calculation above we find that the energy cost decreases from 8,520 to 4,868 SEK, or with 3,652 SEK. New windows are therefore profitable. Just for examining the importance of the so called unavoidable cost it is now assumed that the existing windows have 10 years, instead of 5, left of their life span. The existing LCC will now decrease to 5,931 SEK and the difference in cost with new and better windows will increase to 4,490 SEK. All of a sudden it is no longer profitable to change windows.

Retrofits on the wood-chips transporting system

We calculated the demand for heat in this system to 1,414 W/K, *vide supra.* This demand corresponds to a present value of $\approx$ 575 kSEK. An air-to-air heat exchanger is a natural component to consider in order to save some heat. Assuming that 50% of the losses could be saved it would be possible to invest about 300 kSEK during the 50 year period. It might be possible to find such a component on the market but there are difficulties with such heat exchangers because of the ”contaminated” air flow. Even if we use good filters the heat recovery will rapidly decline because of all wood-dust, which eventually will choke the device. In order to make it operate properly it needs a lot of maintenance which is expensive.

Heating system retrofits

Above it was shown that $\approx$ 100 MWh annually were produced in the boiler in vain. Even with the very low cost of wood-chips, it adds up to 306 kSEK as a present value. We also showed that there are some heating devices run on electricity, such as aero-tempers adding up to approximately 30 kW, electricity heated heating panels of about 5 kW and the domestic water heating system of 7 kW. Even if they are not used very frequently the implications might be large if they are turned on at the same time, and by that produce a severe peak. If it was possible to mend the heating system so these components never have to be used during peak load it could be possible to decrease the electricity subscription from 150 to 100 kW. This will save 23 kSEK, see Table 2, annually and 583 kSEK as a present value. If both systems were operating as they should, large savings could emerge each year. The factory owner can therefore invest a significant amount of money each year and still achieve a positive cash flow.

The measures needed for renovation of the heating system are not suitable to include in a computer program for optimisation. Take for example the malfunctional steam traps. The whole steam system is based upon the idea that steam is transported by its own pressure through the heating devices where condensation must occur. The steam must leave almost all heat in the devices before it by gravitation is transported back to the condensate tank in the form of water. All steam traps must work at the same time because otherwise all steam will flow through the leaking traps and no steam through those which work. If such measures are put into the optimisation program it will only tell you that you must mend the system. They can be thought of as zero/one variables where all of them must be equal to one.

Sensitivity analyses

The Opera–model deals with about ten different measures dependent on the out–door temperature. It is e.g. possible to add extra insulation on the attic and the walls, change windows to triple-glazed types et c. Because of the very low energy price for space heating the Opera–model found that only some window retrofits were slightly profitable and the building should be left almost as it is. This is in total accordance to the result above. By using a computer for all calculations it is easy to change input data. Above we used a 50 year optimisation period, see n in Equation 2. The optimal renovation strategy will, however not change even if n is set equal to 10 years which perhaps is an easier period to fathom. This because of the low cost for wood-chips heating. Because of the poor state of this system, electricity was sometimes used on the margin, i.e. when aerotempers operating by electricity must be used. It is therefore interesting to see what happens if things change. Say that optimisation periods from ten to 50 years are used and the cost for heat is varied from 0.1 to 0.8 SEK/kWh. The result from all these calculations is shown in Figure 9.

From Figure 9 it is obvious that something happens to the LCC, the shape of the surface changes for certain values of the energuy cost and optimisation times. In the left part, and in the front of the 3-d plot we can see that the LCC increases in a linear fashion. For an optimisation time of ten years this linear behaviour is valid all from an energy price of 0.1 SEK/kWh up to 0.9 SEK/kWh. For an optimisation time of 20 years the corresponding ”knee” comes at 0.5 SEK/kWh while it is 0.3 for 30 years. This is so due to the unavoidable LCC and the level of optimal insulation. In the left and front part of the graph extra insulation is unprofitable. Interesting to see is also the amount of insulation which must be applied on the attic floor, see 10 in order to reach optimal conditions.

The influence of the unavoidable LCC is even more spectacular in Figure 10. In the left and front part of the Figure the amount of extra insulation is nil, while it is up to 43 cm in the right part.

Note that the two 3d-plots in Figures 9 and 10 are not viewed from the same spot because of vizualisation reasons.

From this investigation, and by use of the LCC technique in Opera, it is obvious that it is hard to find any profitable retrofits for the climate shield as long as the wood-chips fired boiler works as expected. If for some reason

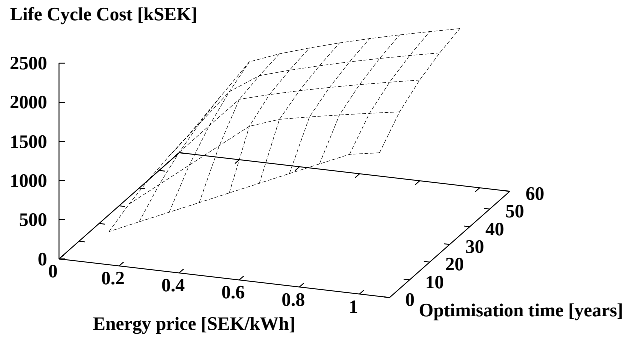

Figure 9: LCC for different combinations of energy costs and optimisation times

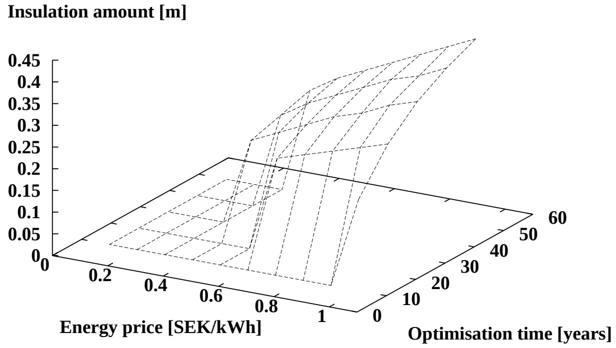

Figure 10: LCC for different combinations of energy costs and optimisation times

this low-operating-cost heating system is abandoned, more expensive systems must be used which in turn makes climate shield retrofits interesting. The important thing shown here is that at least 20-30 cm extra insulation should be implemented, for such a case, in order to reach optimal conditions. Too small an amount will lead to a higher LCC even if the energy demand goes down.

The Opera model also shows what will happen if the factory is connected to a number of alternative heating systems, such as district heating, electricity, natural gas and so forth. District heating, or natural gas are not available in the small Ruda village so these results are not shown here. It has, however, been discussed to abandon the wood-chips boiler and use only electricity for both processes and heating and this case is covered above. Because of European electricity trade the electricity price in Sweden will be the same as in the rest of Europe due to the market forces and hence the price will probably be in the magnitude of 1 SEK/kWh within only a few years. A very bad solution is therefore to abandon the wood-chips boiler and at the same time leave the climate shield as it is.

Conclusions

From the above description it is clear that the existing boiler, which produces steam, has a major role in order to keep the energy cost down. It is also clear that the boiler in its present state is in a poor condition and this is especially true for the steam distribution system. Because of these conditions the company sometimes uses expensive electricity for heating purposes which whithout any doubt could be fulfilled by the steam heating system, at least on ordinary working days. Beacause of fire insurence reasons the wood–chips fired boiler can not be used when people are not present in the factory. In such cases electricity heating must be used but these periods are relatively short. Electric heating might therefore be necessary but it is of vital importance that it does not affect the expensive peak. A load management system is therefore of interest. If wood-chips could be used as the only fuel for heating purposes this implies that all energy conservation measures, such as adding extra insulation on the external walls, must compete in cost with heat coming almost entirely from the wood-chips fired boiler. We calculated this cost to ≈ 0.1 SEK/kWh which must be compared to electricity heating of, at least, four times that cost at present, and perhaps eight times in the close future. Absolutly vital is therefore to get the steam system into a good shape. By adding one new steam trap, at a cost of about 1,500 SEK, we stopped about 80 % of the steam flow through the system which earlier probably were lead outdoors to no vain. Unfortunately, this led to other malfunctions, e.g. in some aero–tempers, so more money has to be invested in the steam system. On the other hand substantial savings are made every day by this very simple and cheap measure so this unspent money can be used for further investment.

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