Available online at www.sciencedirect.com

SCIENCE @ DIRECT®

Energy Conversion and Management 47 (2006) 2223–2239

ENERGY
CONVERSION &
MANAGEMENT

www.elsevier.com/locate/enconman

Refurbishment of industrial buildings

Stig-Inge Gustafsson *

Linköping University, Department of Mechanical Engineering, Division Energy Systems, SE581 83 Linköping, Sweden

Received 25 March 2004; received in revised form 28 June 2005; accepted 12 December 2005
Available online 3 February 2006

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 at 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 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 biomass fired boilers. Such equipment saves environment at the same time it saves money.

Keywords: Industry; Buildings; Steam; Electricity; Processes; Optimisation

1. Introduction

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

---

* Tel.: +46 13 281156; fax: +46 13 281788.
E-mail address: stigu@ikp.liu.se

0196-8904/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enconman.2005.12.011

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 in 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 on oil and low electricity prices, electricity is now in use for purposes such as space heating, drying, hot water heating, etc.

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, led 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 had a small number of 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 the same magnitude throughout the EC, at least in the long run. Electricity is, therefore, likely to become more expensive for Swedish consumers.

2. 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 in 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 burned 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 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 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 the wood chips so this was a crucial question to address.
(4) The cost for different energy conservation measures competes with the 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.

3. The use and cost for electricity

In Sweden, there is now a de-regulated market for electricity. In this system, only one company, the electricity grid owner “Sydkraft Nät AB in our case”, supplies the grid. On the other hand, they have a monopoly,

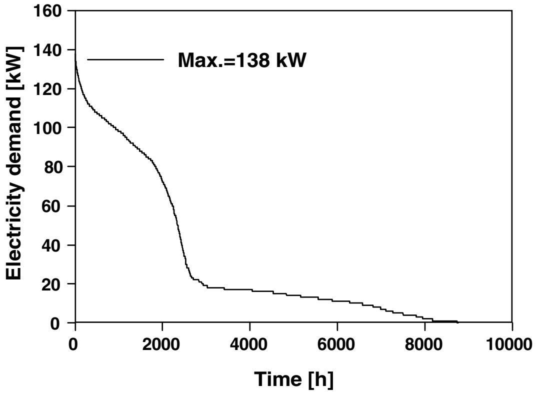

Fig. 1. Duration graph for the electricity use in Bringholtz Furniture Ltd.

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, “Sydkraft Försäljning AB” in our case. 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 with which to make business, i.e. for the actual kilowatt hours. The first company is responsible for monitoring the electricity consumption. It does so by measuring the number of kWh used during 1 h. These values are stored in a memory located in the electricity meter that can be accessed from the Sydkraft computers. The values are subsequently 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, not only a cost for the used kWh but also a cost based on the demand in kW. Below, these costs are studied in close detail just for finding ways to make them lower. The procedure for 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 obtain figures of their electricity use, hour by hour for a full year. In Fig. 1, we have used these values for drawing a so called duration graph where the values are sorted in descending order.

The maximum electricity consumption during 1 h was monitored by the electricity meter to be 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, the demand could have been much higher during e.g. the first 5 min of the hour, but if that were the case, it must have been lower than 138 kW elsewhere. It is also found, see Fig. 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 of 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.

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 registered 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 exceeded. 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 would have 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 exceed 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 occurred two times during the examined year. The first time was April 23. This peak is outside of the winter season, which falls between November and March, and hence, it is not of the same importance as the second peak, occurring November 14. December 16, 1 p.m., another peak occurred. 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 the summer and spring. In theory, each measure that saves 1 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 Fig. 1 shows that the level of 120 kW, which is used as an example, is passed 139 of the 8760 h 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 achieved by saving 984 kWh, and each of these kWh will, therefore, have a monetary value of about 14 SEK. A "normal" kWh has only a

Table 1
Peak load details of the electricity usage at Bringholtz

Date	Time	Energy
April 23	10	138
November 14	12	138
June 03	7	137
November 11	9	137
February 03	12	135
February 03	13	135
November 05	8	135
November 05	9	135
December 16	13	135
February 03	11	134
May 30	8	134
October 27	8	134
November 17	8	134
December 01	15	134
December 08	8	134
December 16	12	134
February 27	9	133
March 26	13	133
April 23	11	133
April 28	14	133
October 27	9	133
November 04	15	133
December 08	9	133
December 12	14	133
February 17	8	132
October 24	11	132
October 27	12	132
October 30	9	132
November 20	13	132
February 03	15	131

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

Type of cost	SEK
Energy cost	82,398
Demand cost, $137 \times P_{av}$	18,700
Subscription cost, winter, $420 \times P$	63,000
Subscription cost, year, $37 \times P_{sub}$	5550
Reactive power demand cost, $205 \times P_r$	6765
Summa summarum	184,413

value of 0.3 SEK, so a peak load kWh has a much higher economic significance than other kWh. Hence, profitable energy conservation is best achieved if it is applied on the most expensive kilowatt hours. 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 were started at 11 on 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.

4. The wood-fuelled steam heating system

A carpentry factory not only produces furniture but also produces a lot of wood residuals, such as wood chips, sawdust and other items 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 Fig. 2. More details on steam heating systems can be found in [2, p. 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 transferred inside the steam pipes out to e.g. an aero-temper. In this apparatus, the steam is supposed to condense into water and, at the same time, leave its latent heat of vaporization. The water passes a so called steam trap, “ST” in Fig. 2, and flows by gravity down to a tank. This tank is not under pressure and to assure this, a pipe is led outdoors. The still warm water is subsequently pumped into the boiler, and new steam is produced. Note that the pump must be able to overcome the pressure in the steam system. After the 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 are not only 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 a tremendous waste of energy, and money.

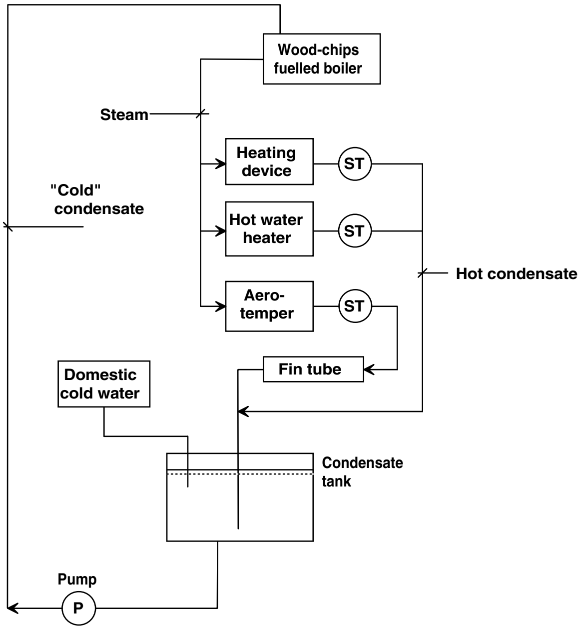

Fig. 2. Principal view of the steam heating system.

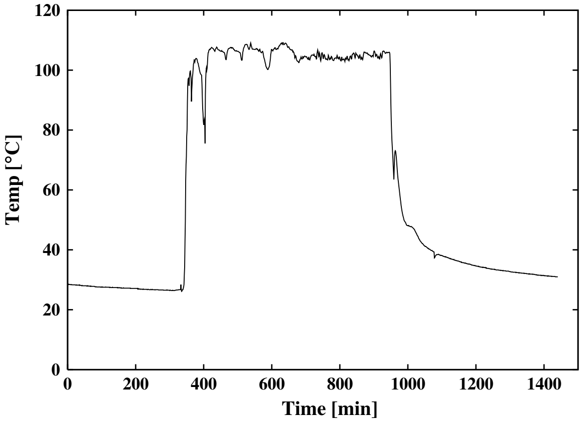

Fig. 3. Surface temperature on the pipe for returning condensate.

This problem was also present in the Bringholtz factory, see Fig. 3, which shows the temperature on the outside of the condensate pipe just before the tank in Fig. 2.

The horizontal 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 min, 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 is because, for atmospheric pressure in the tank, liquid water cannot have a higher temperature than 100 °C. After 10 h, the fire in the boiler is extinguished, and the pipe starts to get cold again.

Because of all the steam flowing down into the tank, the water becomes very hot and the arriving steam cannot fully condense. Hot steam is, therefore, led outdoors with no use at all. This is shown in Fig. 4 where the temperatures on the pipes leading steam from the boiler and water into the boiler are presented.

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 is because the temperature on the pipe increased very fast, e.g. after 1000 min. 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 that opens a valve when water is present. When the water has been

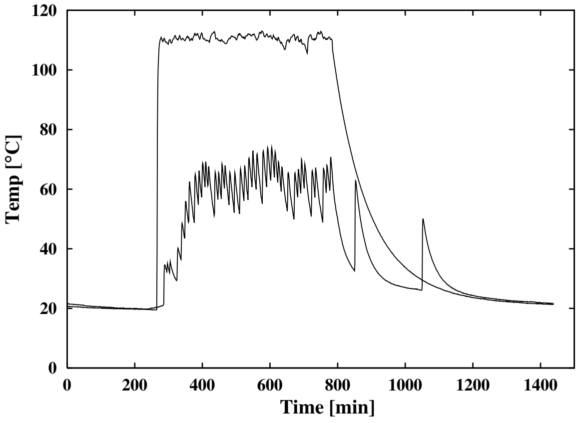

Fig. 4. Temperatures on the surfaces of the steam and water pipes from and to the boiler.

drained, the valve is closed until "new" water is present in the trap. This type was chosen because of its "foolproof" construction. The new trap was installed just before the point where the condensate was led into the tank. Fig. 5 shows the new behavior, cf. with Fig. 4.

By this measure one "chunk" of water pumped into the boiler lasted about 50 instead of 6–9 min. 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 l of water passing through the pipe. In Table 3, the pulses from 1 h are shown.

During one "pumping–batch", about 21 such pulses were registered, equalling 52.5 l of water, see Table 3 at 06.05 and 06.06. The latent heat hidden in 1 l of water converted to steam is 2257 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 ≈6 kWh in one chunk of water. In total, the wood chips boiler, therefore, produces about 40 kWh every time

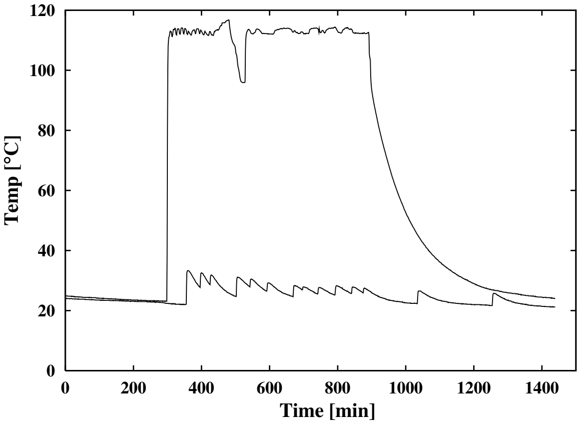

Fig. 5. Temperatures on steam and water pipes with new steam trap.

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

Time	Pulses	Litres
06.05	10	5
06.06	11	27.5
06.11	5	22.5
06.12	12	20
06.13	1	30
06.19	8	22.5
06.20	10	25
06.25	2	5
06.26	11	27.5
06.27	9	22.5
06.33	8	20
06.34	12	30
06.43	9	22.5
06.44	10	25
06.45	2	5
06.49	2	5
06.50	10	25
06.51	10	25
06.57	8	20
06.58	12	30
06.59	2	5

the pump starts. This happens each 6–10 min and implies that the boiler works at 240–400 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, on average, operates at 320 kW. It is in use about 10 h each working day, and hence, 3200 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 used according to the climate and the insulation standard of the building. First, however, some notes on energy conservation measures on buildings are mentioned.

5. 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 dilapidated 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 is actually the best. Fortunately, such a concept exists, and it is called the life cycle cost, abbreviated LCC. The LCC contains all costs that a proprietor must pay during the total life of a building. These costs do not emerge at the same time. 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. According 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 the present time. For a measure, e.g. changing windows in poor condition to new ones, this present value is calculated as:

$$\mathrm{PV}_1 = C_0(1+r)^{-m} \tag{1}$$

where C_0 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 building 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:

$$\mathrm{PV}_2 = C_\mathrm{a}\frac{(1+r)^{-n}}{r} \tag{2}$$

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 of how to calculate the LCC has been around for quite a time, see [4] for an example, but the method had some drawbacks that reduced its popularity. Such drawbacks are e.g. to predict what 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 LCC. 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 the lack of number crunching capacity. With the introduction of personal computers, things changed. The LCC calculations can 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 delve very deep into the inner algorithms of Opera, but Fig. 6, at least, gives a hint on what happens.

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

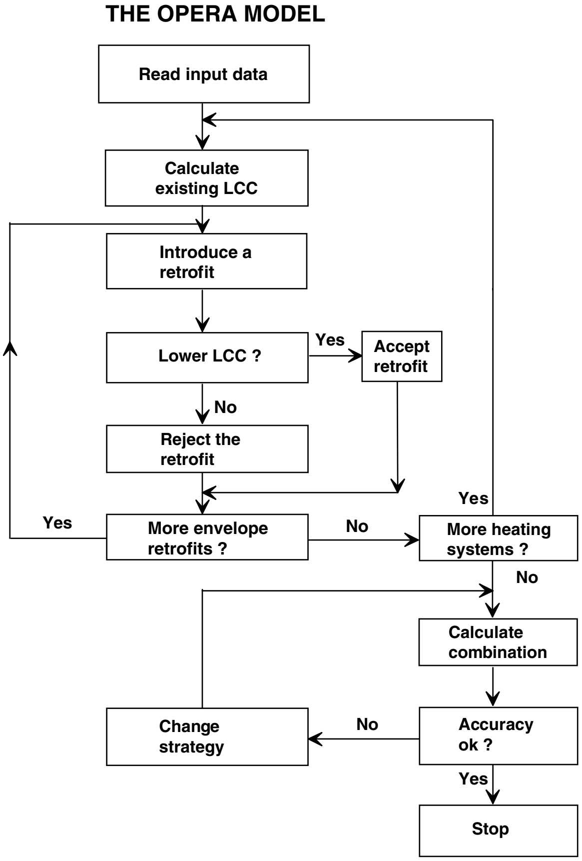

Fig. 6. Schematic view of the Opera model.

building. So far, nothing other than the so called inevitable measures are applied. If it is necessary to install a new boiler after 5 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 etc. All these costs are added, by use of the 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 windows. 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 inclusion in the optimal solution. Now, a new retrofit is tested, e.g. adding extra insulation on the attic floor.

When all such measures that 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 to see if it is profitable. With this new heating system, other candidates are chosen and the heating system is once again changed. Eventually, we have a number of heating systems with different sets of possible candidates for affecting the demand in the building. The program now chooses the set that 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 when 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 the 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 premises 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 is actually needed in the factory.

6. Calculation of the energy demand

The carpentry factory was established in 1926. Some parts of the factory are of that age, but other parts are newer. The older parts are, nowadays, used mostly as storage for products, and hence, the temperature in those parts is 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 the 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 construction results in a U-value of about 0.5 W/m^2 K if no extra insulation is applied. Nowadays, such a high U-value is not applicable, but the standard of this part of the building was set in 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 3000 m^2, the wall area to 1200 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 3350 W/°C, see Table 4.

All carpentry factories have a system for wood residuals transport. Saw-dust, wood-chips and other fractions of the processes are transported to the bin for wood fuel using a fast 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 settle 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 machineries 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 indoor 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 actually to monitor the flow of

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

Building part	U-value	Area	$U \times A$
Attic floor	0.5	3000	1500
Floor	0.3	3000	900
Walls	0.5	1200	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	–	–	3350

this returning air because of the 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 h a day. This is not the fact in an industry. Here, it is, therefore, assumed that the ventilation rate is reduced to 23% or 4300 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

$$Q = c_p \rho v \frac{1000}{3600} \tag{3}$$

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

$$Q = 1.0057 \times 1.1774 \times 4300 \times 1000/3600 = 1414$$

Because of some further approximations necessary for the computer program the value actually used was 1465 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.

The indoor temperature in the factory differs depending on 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 h, so the number of degree hours, DH, is calculated to:

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

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 were used each month.

The demand for electricity during one full year is approximately 300 MWh. Assuming that about 75% of this energy is transferred to heat inside the premises, the free heat from appliances 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 values, 3350, and the value for ventilation, 1465, yields the number of kWh that 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,

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

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

Table 6
Heating demand calculations in kWh for the Bringholtz factory

Month	Deg. h.	Heating d.	Hot water	Free heat	Solar	Fr. boiler
1	17,632.8	84,899.3	2000	18,000	982.2	67,917.1
2	16,060.8	77,330.3	2000	18,000	1966.6	59,363.7
3	16,368	78,809.5	2000	18,000	4347.9	58,461.6
4	12,168	58,587.1	2000	18,000	6171.4	36,415.7
5	9076.8	43,703.4	2000	18,000	8545.6	19,157.8
6	5400	26,000.2	2000	18,000	8822.6	2000
7	3571.2	17,194.8	2000	18,000	8667.1	2000
8	4240.8	20,418.8	2000	18,000	7391.3	2000
9	6984	33,626.9	2000	18,000	5401.8	12,225.1
10	10,713.6	51,584.4	2000	18,000	3037.2	32,547.1
11	13,248	63,787.1	2000	18,000	1230.8	46,556.3
12	15,698.4	75,585.4	2000	18,000	653.7	58,931.8

i.e. 18,000 kWh, and solar insolation, i.e. 982 kWh. However, 2000 kWh must be added for heating 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 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 of 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 maintain 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.

7. 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 for 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 have here a dual fuel system. Fire insurance regulations prohibit the use of the boiler when no human beings 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 is actually used.

7.1. 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 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 4500 kcal/kg, i.e. 5.23 kWh/kg. If wood contains some moisture, this calorific value decreases, and for a moisture content of 10%, 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 at 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 of wood chips each year, while there was a demand for 365 MWh from the boiler, *vide supra*. The company must produce a lot more than 15 MWh of 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 to consider. One of the employees

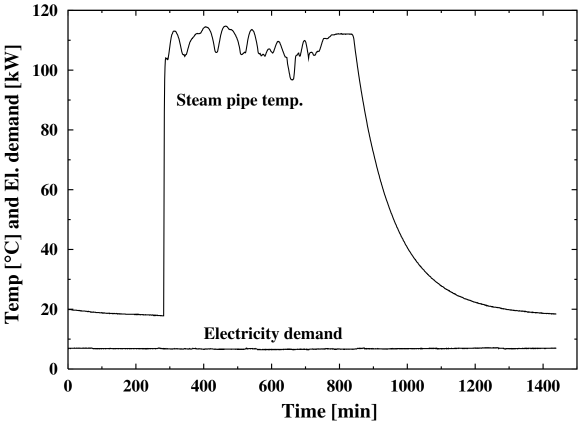

Fig. 7. Electricity demand in the domestic hot water heater and temperature on the main steam pipe.

must take care of all maintenance and operation of the boiler. This cost has been estimated to be 60 kSEK each year. This will certainly make the use of the boiler less profitable, but the cost is only in part dependent on the produced number of kWh.

7.2. 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 Fig. 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 reaches a high level, e.g. over 100 °C, the electricity demand should be zero, i.e. the electric heating should be turned off. Fig. 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 they seemed to operate as they should. The company also has some aero-tempers of the size 10 kW, but they were seldom 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.

8. Calculation of the life cycle cost

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

8.1. 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 3000 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, etc. are located. In the second group, C_2, are 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:

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

where t equals the thickness of the 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 Fig. 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 utmost 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 the extra insulation is t, the new U-value becomes, see [9]:

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

For mineral wool, the value of k equals 0.04 W/m^2 K 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 cost for insulation, see Eq. (4), will increase. At a certain point, the total cost is the smallest possible, i.e. optimal conditions prevail, see Fig. 8.

In Fig. 8, the insulation cost has been calculated from Eq. (4) multiplied with the attic floor area, 3000 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 Eq. (5) multiplied by the attic floor area, the number of hours for one full year, 8760, the temperature difference between the indoor temperature, 22 °C, and the average mean outdoor temperature, 7 °C and the cost for heat from the wood chips fired boiler, 0.12 SEK/kWh. The annual cost has subsequently been used in Eq. (2) with $n = 50$ and $r = 0.03$. In Fig. 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 ≈500 kSEK, and compare with the LCC if insulation is applied, which is of the magnitude 1200 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. setting the value of the derivative of a continuous function to zero.

8.1.1. 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

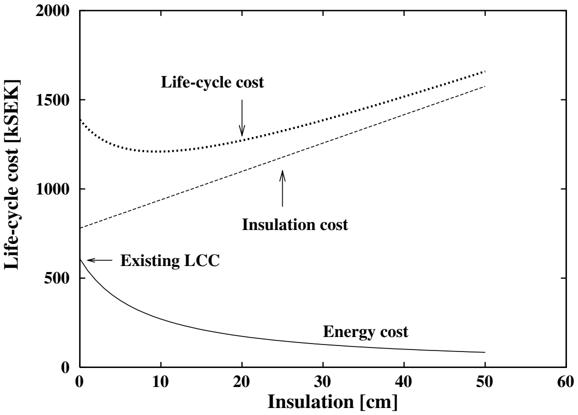

Fig. 8. Insulation optimisation of the attic floor.

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 1100 SEK/m^2, while a triple glazed window had a cost of 1300 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 would 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 6600 SEK, while the triple glazed type costs 7800 SEK. It is further assumed that new windows have a life span of 30 years. We now use Eq. (1) in order to calculate the existing LCC where the present windows are changed into similar double paned windows. We get:

$$6600 \times (1+0.03)^{-5} + (1+0.03)^{-35} - \frac{15}{30}(1+0.03)^{-50} = 7286$$

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

$$7800 \times (1+0.03)^{-0} + (1+0.03)^{-30} - \frac{10}{30}(1+0.03)^{-50} = 10,420$$

The difference in cost is 3134 SEK. With the same input data as for the insulation calculation above, we find that the energy cost decreases from 8520 to 4868 SEK, or 3652 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 5931 SEK, and the difference in cost with new and better windows will increase to 4490 SEK. All of a sudden, it is no longer profitable to change windows.

8.1.2. Retrofits on the wood chips transporting system

We calculated the demand for heat in this system to 1414 W/K, vide supra. This demand corresponds to a present value of ≈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 the wood dust, which eventually will choke the device. In order to make it operate properly, it needs a lot of maintenance, which is expensive.

8.1.3. Heating system retrofits

Above, it was shown that ≈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 were 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 the heat in the devices before it, by gravity 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 will flow through those that 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.

8.2. Sensitivity analyses

The Opera model deals with about 10 different measures dependent on the outdoor temperature. It is e.g. possible to add extra insulation on the attic and the walls, change windows to triple glazed types etc. 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 with 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 Eq. (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 is 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 10 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 Fig. 9.

From Fig. 9, it is obvious that something happens to the LCC, the shape of the surface changes for certain values of the energy 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 10 years, this linear behaviour is valid for all energy prices from 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 also is the amount of insulation that must be applied on the attic floor, see Fig. 10, in order to reach optimal conditions.

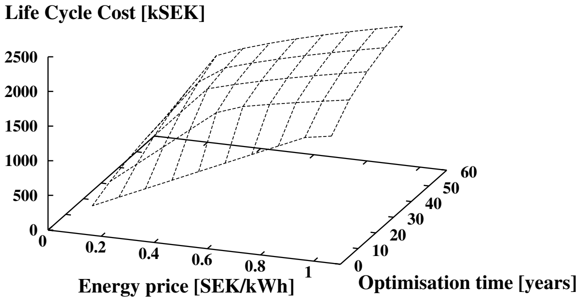

Fig. 9. LCC for different combinations of energy costs and optimisation times.

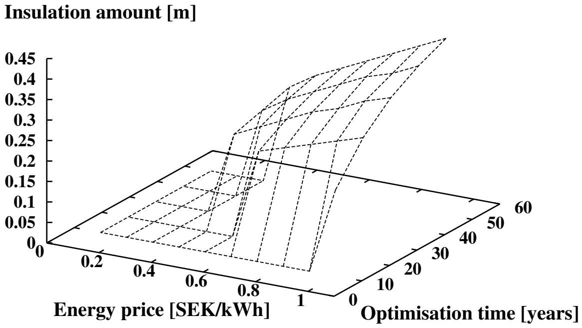

Fig. 10. Optimal insulation amount for different combinations of energy costs and optimisation times.

The influence of the unavoidable LCC is even more spectacular in Fig. 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 3-d plots in Figs. 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, 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 the 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.

9. 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, without any doubt, could be fulfilled by the steam heating system, at least on ordinary working days. Because of fire insurance reasons, the wood chips fired boiler cannot be used when people are not present in the factory. In such cases, electrical 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 be ≈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 near future. Absolutely vital is, therefore, to get the steam system into good shape. By adding one new steam trap, at a cost of about 1500 SEK, we stopped about 80% of the steam flow through the system, which earlier probably were led outdoors to no avail. 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.

References

[1] Gustafsson SI, Rönnqvist M, Claesson M. Optimization models and solution methods for load management. Int J Energy Res 2004;28(4):299–317.
[2] Turner WC. Energy management handbook. Wiley Interscience; 1982.
[3] Çengel YA. Introduction to thermodynamics and heat transfer. USA: McGraw-Hill; 1997.
[4] Marshall HE, Ruegg RT. Energy conservation through life-cycle costing. J Architect Educ 1976/1977;30(2).
[5] Gustafsson S-I, Karlsson BG. Life-cycle cost minimization considering retrofits in multi-family residences. Energy Build 1989;14(1):9–17.
[6] Massey BS. Mechanics of fluids. 5th ed. UK: Van Nostrand Reinhold; 1983.
[7] Holman JP. Heat transfer. 8th ed. USA: McGraw-Hill; 1997.
[8] Kollmann FFP, Côté WA. Principles of wood science and technology. Springer Verlag; 1984.
[9] Gustafsson S-I. Optimisation of insulation measures on existing buildings. Energy Build 2000;33:49–55.