SIMULATING LIFE CYCLE COST FOR INDOOR CLIMATE SYSTEMS

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ABSTRACT

The indoor climate system, which serves a building with a proper indoor air quality and thermal comfort, has been predominantly designed based on the initial cost. A life cycle approach could improve both the economic and environmental performance. For example, the energy use could decrease. There has been a lack of knowledge, models and simulation tools for determining the life cycle cost (LCC) for an indoor climate system. The objective of this paper is to present a model for calculating the LCC for indoor climate systems. Focus is on indoor climate systems for premises and dwellings. Prices are from Sweden. The model is a result from a research project reported in a doctoral thesis where the LCC model is presented in detail and input data and indoor climate system design is analyzed.

KEYWORDS

LCC, Life cycle cost, energy use, costs, indoor climate systems, ventilation

INTRODUCTION

Background

People spend up to 90% of their time indoors (Sundell and Kjellman, 1994; Lech et al. 1996). Most of our time indoors is divided between work and home with the remainder being in for example premises, shops and vehicles. To ensure people's health and comfort when they are indoors, the indoor air quality and thermal comfort must be appropriate. An indoor climate system serves this purpose (Nilsson, 2003; Goodfellow and Tähti, 2001; Boverket, 2002).

In the context of this paper, the indoor climate system consists of ventilation, heating and cooling systems to provide a building with a good thermal comfort and indoor air quality. In a particular situation, several different indoor climate systems can most often be used. Figure 1 shows a normal indoor climate system for an office building in Sweden. Due to demands such as the EU Directive on the Energy Performance of Buildings or the Kyoto protocol, the ability to only handle the functional requirements is not enough. The indoor climate system must also use as little resources as possible, where energy is one type of resource. As a general rule, the built environment sector in Sweden currently uses about 40% of the total energy used in the country. Most of this energy is used to provide buildings with the energy required for heating, ventilation and cooling.

Specifications for the indoor climate regarding thermal comfort and air quality are determined by requirements, recommendations, national regulations, or by the building's user. This helps to simplify the design process of an indoor climate system. Usually, the minimum and maximum temperatures and the supply airflow rate are set depending on the activity in the building.

One problem in the design of an indoor climate system is that there has been a predominant focus on initial costs. A life cycle approach could improve both the energy and economic performance of the indoor climate system. Even though many actors are present with different economical interests in different parts of the building process and the building's life cycle, the interest for life cycle cost analyses seems to have increased over time.

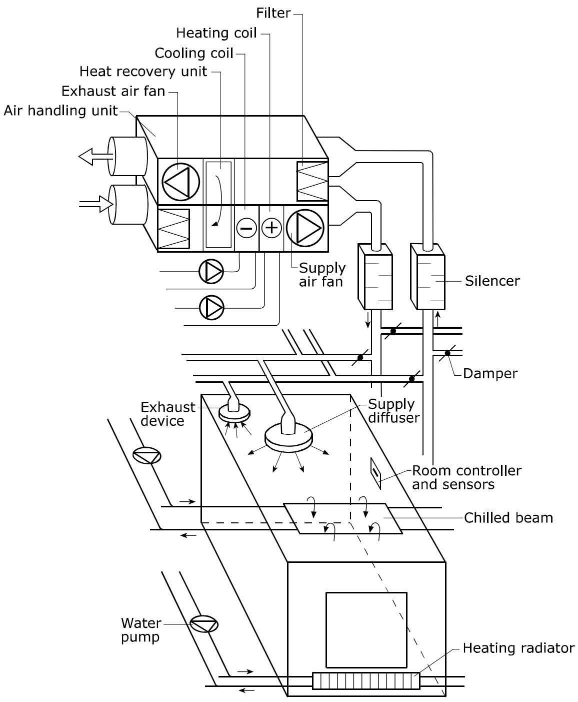

Figure 1 A typical indoor climate system with radiant heating, chilled beams and a supply and exhaust ventilation system with a heat recovery unit.

The Life Cycle Cost (LCC) is the sum of all costs during the entire life cycle of the indoor climate system. The LCC can be a basis for comparisons between different indoor climate systems and system designs. There are a number of programs and some helpful literature for calculating LCC. However, there is a lack of models and tools specifically produced for calculating the LCC for indoor climate systems during the early stage of the building design process, which is when the indoor climate system should be designed.

A number of LCC models are available and some are for indoor climate systems. However, many of them handle only a part, or some parts of the indoor climate system. In Sweden, a model for doing an LCC analyses on a routine basis is called “LCC Energi” (Sveriges Verkstadsindustrier, 2001). “LCC Energi” handles a number of details in the air handling unit, such as heat recovery unit efficiency and a correction term for freezing in the heat recovery unit. Still, external programmes for calculating the initial costs of the system, the energy demand, and pressure drops are needed.

Using ideas from LCC Energi, an EU-supported project has drawn up similar guidelines, a SAVE project, known as “LCC-based Guidelines on Procurement of Energy Intensive Equipment in Industries” (Eurovent, 2001), which adopts the manufacturer’s point of view instead of that of the client or building owner. One problem with both sets of guidelines is the lack of options for modelling either the entire indoor climate system or different control strategies.

A PC programme that performs LCC analysis was presented by Ruegg and Petersen (1985). This programme calculates the LCC and a number of other economic factors. However, since it does not focus on indoor climate systems, it requires a problem definition and a definition of the alternatives by the user. James and Phillips (1992) presented a spreadsheet application for the purpose of separating the HVAC system from the building, but it does not calculate the energy demands or different HVAC systems. Lutz et al. (2005) discussed LCC analysis of residential furnaces and boilers. They showed that a reduction of LCC was possible with more efficient products. A number of different economic techniques, regarding LCC for insulation materials depending on thickness, were discussed by Al-Hammad and Fahd (1992). One of the preferred techniques was the net present value method. Often, constant maintenance and repair costs are assumed in LCC analyses. Karyagina et al. (1998) stated that these assumptions often lead to over-simplifications in the LCC analysis and incorrect results.

Vik (2003) looked at the life cycle costs for hybrid ventilation systems. They incorporated the building in a higher extent than mechanical systems. He compared different solutions, also with a typical mechanically ventilated building, and described a method to calculate LCC. Since the building structure and envelope is a part of the ventilation, he discusses cost allocation a lot. The result showed no large difference between mechanical and hybrid ventilation systems.

Objectives and limitations

The objective of this paper is to present a model to do LCC calculations on indoor climate systems early in the building design process. The LCC should basically be done in the context of the building owner. To enable the use of the model at an early stage in the building design process, the need for input data should be reasonably low. The model handles different systems that are common in Sweden and different control strategies for these systems. The buildings that are taken into account are residential buildings, office buildings and school buildings. All indoor climate systems must fulfil general requirements to get an appropriate indoor climate. The model program is a result from a research project reported in the author’s doctoral thesis (Johansson, 2005) where the LCC model is presented in detail and questions about input data and indoor climate system design are addressed in seven appended papers.

This LCC model does not deal with some of the problem areas of modelling the LCC for indoor climate systems

- Life Cycle Assessment (LCA) is something else and not dealt with here.
- The LCC technique is used as a tool and not evaluated further.
- The LCC model does not include an analysis of the energy supply system. Therefore, the energy supply system is modelled in a simple way.
- There are a lot of different indoor climate systems. Only a limited number of systems are reasonable to include. Since the focus of this project has been the building industry in Sweden, indoor climate systems, buildings, prices and outdoor climates are from a Swedish context. The approach used could be applied to other locations.
- The differences between manufacturers of indoor climate system components are not analyzed. Therefore, products from several manufacturers spread over the Swedish market are used for input data.
- Natural and hybrid ventilation systems are not considered, as they are already the subjects in a number of theses (Jenssen, 2003; Kleiven, 2003; Vik, 2003).

- Industrial buildings are not considered, since they depend on the industrial process. Therefore, they are difficult to generalize.
- The building design and technology will influence not only the costs of the indoor climate system but also the costs of the building itself. The change in building costs will not be considered in the LCC model, which means that the LCC model can not optimise the indoor climate system together with the building. For example, thicker insulation in a dwelling should lower the amount of energy used for heating thus lowering the power need for heating. This would result in smaller and less expensive indoor climate system components but would increase the cost of insulation. This LCC model takes into account the influence on the indoor climate system components and on the energy use for heating but it does not take into account the higher insulation cost.

List of symbols

Quantity	Description	Unit
C	Occurring cost	SEK
C_{duct}	Cost for ducts	SEK
d	Diameter of duct	m
L_{duct}	Length of ducts	m
N	Life span	year
n	Time	year
NPV	Net present value of cost	SEK
NPV_n	NPV of recurring costs	SEK
P_{air}	Power for heating ventilation air	W
P_{cap}	Power from thermal mass to room	W
P_{fan_ex}	Electrical exhaust fan power	W
P_{fan_sa}	Electrical supply fan power	W
P_{int}	Internal power gain	W
P_{HP_gain}	Gained power from heat pump	W
P_{HP_in}	Electrical input power to heat pump	W
P_{leak}	Outgoing power caused by leakage	W
P_{solar}	Power gained from solar radiation	W
$P_{support}$	Power from support cooling, heating	W
P_{trans}	Power transmitted from room	W
P_{vent}	Power from supply air to room	W
q_{leak}	Leakage airflow rate	m^3/s
q_{vent}	Ventilation airflow rate	m^3/s
r_c	nominal price change rate	-
r_d	discount rate of interest	-
r_n	nominal rate of interest	-
r_p	real price change rate	-
r_r	real rate of interest	-
t_{cap}	Temperature of thermal mass	°C
t_{ex}	Exhaust air temperature	°C
t_{hr_in}	Temperature after heat recovery unit	°C
t_{hr_out}	Temperature after heat recovery unit	°C
t_{out}	Outdoor temperature	°C
t_{room}	Room temperature	°C
t_{sa}	Supply air temperature	°C

METHODS

Methodology

This LCC model is based on a theoretical approach. It uses empirical data for components that are put together to form different indoor climate systems. Typically defined components can be split into subcomponents. These components can also be grouped together to form super components. The question is on what level the components should be specified. Components that are too large would hide differences that affect the LCC. Components that are too small would need a lot of data and would not be needed to separate the different indoor climate systems from each other. By this approach, parameters such as outdoor climate can be handled by the simulation. If the components are small enough, the use of the LCC model can result in simplifications being made in order to get a less detailed model. This would be difficult to test without first having the detailed model.

An alternative approach would be to use measured data from empirical objects, which means real buildings. That would provide realistic data, at least for the particular object where the data came from. The question is if such data are generally valid. Since different systems will be compared, there is a need for data from buildings including the comparison of indoor climate systems. For stochastic reasons, there would be a need for a number of buildings with each indoor climate system. It would be difficult to find enough valid or reliable objects with traceable costs for each part of the indoor climate systems to obtain significant results. The multitudes of parameters that influence the life cycle cost need to be matched with the collected cases, which yields a lot of cases to collect data from. This seemed to be an impractical way. It would also be impossible to test non-existing indoor climate systems.

Physical boundaries	**Outdoor climate**
	Building data
User boundaries	**Use of the building**
	Demands on the indoor
Options	**Indoor climate systems**
Design	**Energy use**
	Power need
Starting costs	**Initial**
Future costs	**Energy**
	Maintenance
	Repair
	Demolition
	Other
Economy	**LCC analysis**

Figure 2 The parameters and costs of the model. Together, these costs make up the life cycle cost.

A main problem when life cycle cost analyses are performed is to determine which costs should be included or not. Figure 2 shows the costs included in this model and what input data is needed. The outdoor climate, the building data and the use of the building are assumed to be given. Demands on the indoor climate usually mean that there is a certain temperature span and a certain airflow rate. These conditions result in a number of possible indoor climate systems for the particular situation. For each one of these applicable indoor climate systems, the energy use and maximum power demand are calculated. The maximum power demand sets the size of the components which means the initial cost for purchasing and mounting the system can be calculated, as well as maintenance costs and repair costs. Demolition costs are neglected. Other costs are costs influenced by the indoor climate system. The model includes the costs of the user's productivity related to the airflow rate and temperature. Discounting future costs to the net present value and summing eventually gives the life cycle cost.

Buildings

This LCC model incorporates offices, schools, apartment buildings and detached houses of different sizes with typical layouts. The typical building layouts have been set up with help from consultants working with building services and Wikells byggberäkningar AB (2003).

A typical Swedish office or school floor layout is shown in Figure 3. In Figure 3, there is a middle section of the building surrounded by two corridors and two rows of rooms in the perimeter of the building. This floor layout can also be set up with one corridor with rooms on each side, or one corridor with rooms only on one side, which is common in schools. The rooms can be differently sized but the two general types of rooms in premises are office cells and assembly rooms in the form of conference rooms and classrooms. They have different sizes and use.

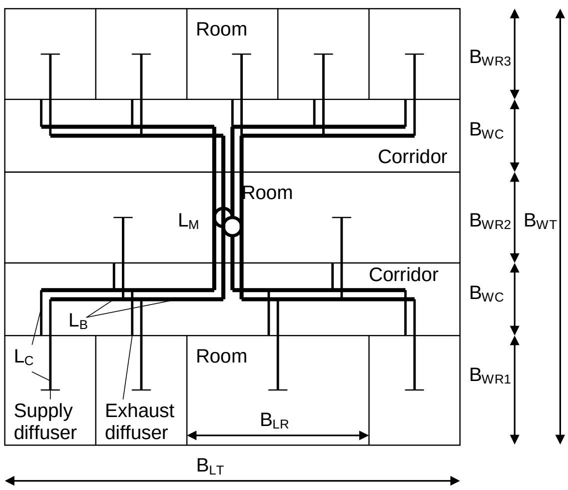

Figure 3 A floor layout for offices or schools with two corridors. In between the corridors, there are usually conference rooms. Rooms, for example office cells, are located on the envelope side of the corridors.

Each room is assumed to have supply air. Exhaust air can be taken from each room or from the corridor on each storey. In the figures of the layouts, the buildings are straight but they can also form bends, circles or other curves as long as they have windows in each room. Toilets, wardrobes and other such rooms have not been modelled to simplify the need for input data. The difference in costs for such parts caused by the choice of indoor climate system should be small.

Apartment buildings are assumed to have the same layout on all storeys. Apartments are spread out as slices along the width of the building and the length corresponding to the apartment area. Inside the apartment, there are a different number of rooms depending on the apartment size. Figure 4 shows this layout. The rooms with supply devices are the rooms that are not kitchens or bathrooms. Exhaust devices are located in the kitchen and in the bathrooms.

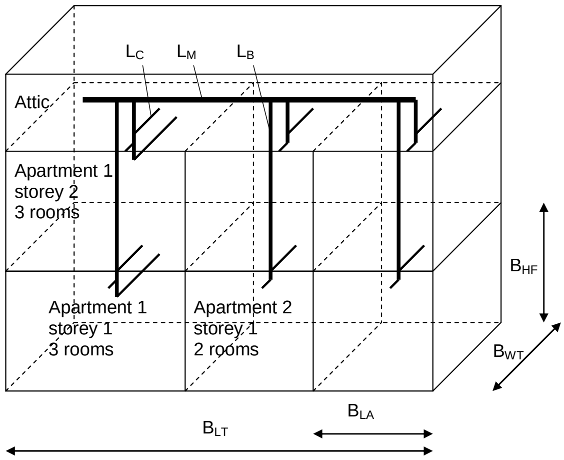

Figure 4 The assumed typical apartment building seen in orthogonal perspective oblique from above. Only one duct system is shown to make the picture readable.

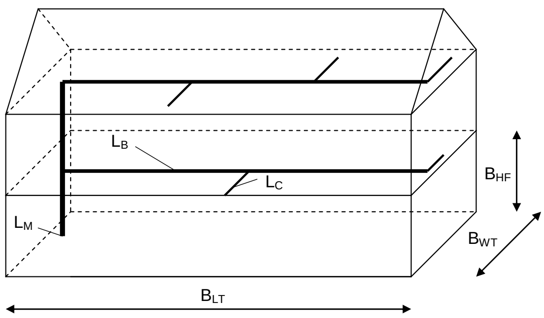

Figure 5 The assumed typical detached house seen in orthogonal perspective oblique from above. Only one duct system is shown to make the picture readable.

Detached houses are supposed to have one, two or three storeys. The rooms with supply devices are the rooms that are not kitchens, bathrooms, toilets or wardrobes. These rooms have supply diffusers or air inlets. Bathrooms, toilets, laundry rooms, kitchens and wardrobes have exhaust air. Figure 5 shows a detached house.

Details about duct lengths, pipe lengths and number of rooms in detached houses can be found in

Johansson (2005). The rooms can be sized differently for each of the four modelled zones.

Indoor climate systems

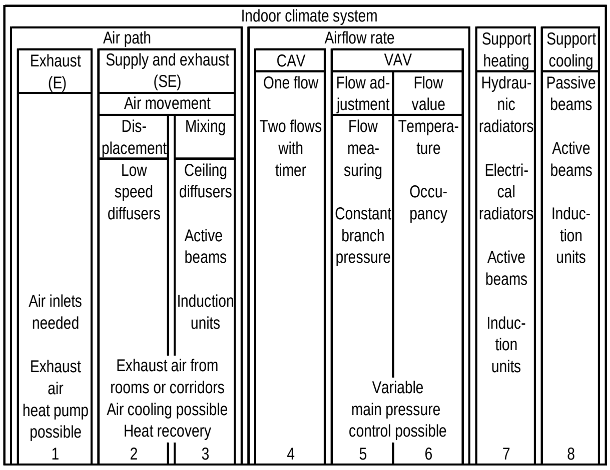

Figure 6 Systems included in the life cycle cost model. CAV means constant airflow rate and VAV means variable airflow rate. An example of an indoor climate system is active beams from column 3 with exhaust air in the corridor combined with timer controlling two airflow rates from column 4. Active beams from column 8 and hydronic radiators from column 7 can be added.

Figure 6 shows the included indoor climate systems. Indoor climate systems, which are a subset of building services, are subdivided into the groups “Air path” (through the building), “Airflow rate”, “Support heating” (heating excluding supply air) and “Support cooling” (cooling excluding supply air). One element from each of these subdivisions must be included to form an indoor climate system. Below the horizontal lines in Figure 6, more subdivisions are listed, if any, and then the different kinds of components are listed. The number of possible combinations of indoor climate systems from Figure 6 is 1680, but some are not applicable or realistic, for example temperature controlled variable airflow rate (VAV) in combination with support cooling.

To simplify and avoid valuing the benefit from a certain level of the indoor climate, it can be assumed that the indoor climate system must accomplish correct indoor temperatures and a sufficient outdoor airflow rate. The LCC model uses an airflow rate per floor area plus an airflow rate per person. The requirements are expressed in l/(s•m²) and in l/(s•person). From the Swedish building code (Boverket, 2002), Enberg (1995) interpreted the recommended flow rate for dwellings to be 0.35 l/(s•m²) and for schools and offices to be 0.35 l/(s•m²) + 7 l/(s•person) and this is still used in practice. Concannon (2002) gives required airflow rates for a number of different countries.

Initial costs

The initial cost is defined as the cost that occurs in the beginning of the life cycle, at time zero. The terms installation cost or first cost are also used in literature. The initial cost consists of the cost for material for the indoor climate system components and the labour cost for mounting them. That incorporates duct system components, air terminals, air handling unit, fire dampers, silencers, control equipment, water pipe system, support heating and cooling components and adjustment of duct systems and pipe systems. It is also possible to input the costs for electrical, heating and cooling plants into the LCC model.

To be able to find costs for all components, the indoor climate system components must be dimensioned, with help of the power balance. This is due to the fact that component costs are usually a function of the size of the component and the size of the component is a function of the power it should generate or the airflow rate it should provide. Since this paper focuses on Swedish conditions, costs in Sweden have been used. The approach should be possible to use in other countries but the figures need to be changed. Wikells byggberäkningar AB (2003) has cost databases for the building industry based on empirical data. They present costs including labour for different components and systems for buildings.

The implementation of cost data can be in the form of cost lists for different sizes of the components or in the form of curve fits based on the cost lists. For duct system components, the curve fits of the cost are used to be able to test non-standard sizes for duct systems. That decreases the need for data particularly regarding the T-junctions that can be many sizes. For silencers, a curve fit is also used to avoid too much data for different sizes. The same approach is used for radiators and beams. For other components, costs lists are used based on their discrete sizes.

Wikells does not correct for the number of bought components. On the other hand, actors in the building sector can be thought to know how to handle the prices of Wikells since it is a well known cost calculation system. It also seems to be common with deductions on components. Therefore, a possible deduction can be inserted in the LCC model.

An example of initial costs in SEK excluding VAT is given by Equation 1, which gives the cost for ducts. Lists of all needed component costs are given by Johansson (2005).

$$C_{duct} = L_{duct}\left(125 + 1300 \cdot d^{1.19}\right) \qquad (1)$$

Power balance and energy costs

The energy cost is usually a major part of the running costs. The energy cost originates from the energy use of electricity, heating and cooling. There is also a power related cost within the heating and cooling plant, the electrical installation and the needed components in the indoor climate system. Therefore, both maximum power need and annual energy use must be calculated by the LCC model.

The energy use is calculated by integrating the power balance for each hour of the year based on hourly outdoor climate data. Figure 7 shows the room, the air handling unit (AHU) and the modelled powers with needed temperatures. The room must be in power balance according to Equation 2 and the air handling unit together with the plants must provide the balancing powers $P_{support}$ and P_{vent}. The terms of the power balance are discussed in EN ISO 13790:2003. The problem is to tell how much bought energy and maximum power is needed to supply the sufficient $P_{support}$ and P_{vent} to get the desired t_{room} and q_{vent}.

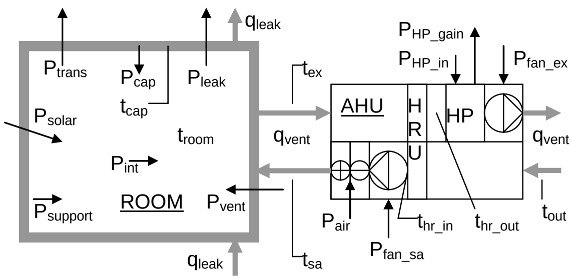

Figure 7 The included powers in the power and energy calculation of the LCC model.

All terms in Equation 2 are explained by Johansson (2005). The model needs outdoor climate data on hourly basis which is obtained from the computer program Meteonorm (Meteotest, 2003). The heat gain of the building's interior is modelled by a single heat capacitor inside the room. All loads can vary over time. The efficiency of fans and air handling units (AHU) is modelled and is dependant on pressure drop, airflow rate and unit size. The air leakage is assumed to be constant over time depending on the indoor pressure. The four modelled zones can have different data in the room but are assumed to be connected to the same air handling unit.

$$P_{support} = P_{trans} + P_{leak} - P_{int} - P_{solar} - P_{vent} - P_{cap} \qquad (2)$$

Maintenance, repair, space loss and demolition costs

Maintenance is defined as the cost that occurs annually for maintaining the indoor climate system. That includes filter change and some overhaul of the equipment, cleaning and mandatory ventilation control in Sweden. Change of components after their particular life time is defined as repair cost. Scrap value is the costs that the indoor climate system can be sold for at the end of the life cycle. The scrap value can be negative if it costs money to get rid of the scrap. The scrap value can most often be neglected if it occurs far in the future.

Other costs

Other costs are costs that are influenced by the choice of indoor climate systems or by the choice of parameters in the indoor climate system. An example is performance costs such as productivity or health costs depending on the airflow rate or indoor temperature, which the proposed model includes.

Life cycle costs

The life cycle cost of a product is the sum of all costs occurring related to that product over its entire life span. Future costs are discounted to the value of today, the net present value, by the use of a discount rate of interest. A cost that occurs in the future can be paid for by a smaller amount today if the discount rate of interest is positive because the money can be in the bank and grow to exactly cover the cost when it will be paid. Equation 3 gives the net present value of a future cost occurring at year n. Equation 4 gives the net present value of equal costs occurring every year for N years except the first year. This is typical for recurring costs for indoor climate systems like energy or maintenance. Equation 5 describes the discount rate of interest. It is reasonable to believe that the real price change rate of energy will be positive, which has been the case for a number of years.

$$NPV_n = \frac{C}{(1+r_d)^n} \qquad (3)$$

$$NPV = C\,\frac{(1+r_d)^N - 1}{r_d \cdot (1+r_d)^N} \qquad (4)$$

$$1 + r_d = \frac{(1+r_n)}{(1+r_c)} = \frac{(1+r_r)}{(1+r_p)} \qquad (5)$$

Software and algorithmic aspects

To apply this LCC model into a PC program, there must be an order to the calculations and decisions to end up with the LCC. The following steps were used:

1. Collect input data about the economics, the building and the system. Collect input data on the outdoor climate for the normal year on the actual location.
2. Set all duct and pipe piece lengths according to the building's geometry and the chosen system.
3. Set the occupancy levels of all four modelled zones to 100%. The cooling design is supposed to handle full occupancy.

4. Perform an annual energy use calculation for each zone on hourly basis with 100% occupancy to obtain the maximum airflow rate in variable airflow rate systems and the maximum cooling power.
5. Sum the airflow rates for each storey, if exhaust air devices are used only in the corridors.
6. For each room, decide the size of each diffuser to handle the maximum design airflow rate.
7. For the hour with highest total airflow rate, calculate the maximum pressure drop in the duct systems with the air terminals. This pressure drop is the design pressure drop. In a VAV ventilation system without main pressure feed back, this design pressure drop is supposed to be maintained constantly by the air handling unit. In the case of a CAV ventilation system with timer, the main pressure is decreased during nights. In that case, the maximum pressure drop for the lower airflow rate must also be calculated.
8. Set the occupancy levels to zero. Perform an annual energy use simulation and find the maximum power needed for heating. The heating design is supposed to handle an empty building.
9. Set the sizes of all components with regards to the dimensioning values.
10. Reset the occupancy levels to the estimated levels for the zones respectively.
11. Calculate the annual energy use on an hourly basis for each zone.
12. Sum the airflow rates for every hour for the zones and calculate the needed energy to exchange the air and heat or cool the supply air. The pressure drop must be calculated for every hour if a variable airflow rate system with constant branch pressure and main pressure feed back is used.
13. Sum the costs for the components associated with and necessary for the chosen system. Calculate energy, maintenance, space, repair and other costs.
14. Use the LCC technique on the calculated initial and future costs to obtain the LCC.

The needed algorithms are all without internal iterations for solving implicit equations. In the case of CAV ventilation system without support cooling, there is no need to run the cooling power design part. To be able to compare different systems, several calculations are needed. Optimisation of parameters such as size of the air handling unit or pressure drop per meter duct also requires several calculations.

RESULTS

Figure 8 gives the resulting LCC for an office system, three school systems, a multi-family apartment system and a single family house system respectively. The life span has been 40 years and the discount rate of interest 1% for electricity, 2% for heat and 3 % for other costs to represent that the heat and electricity have a real price increase.

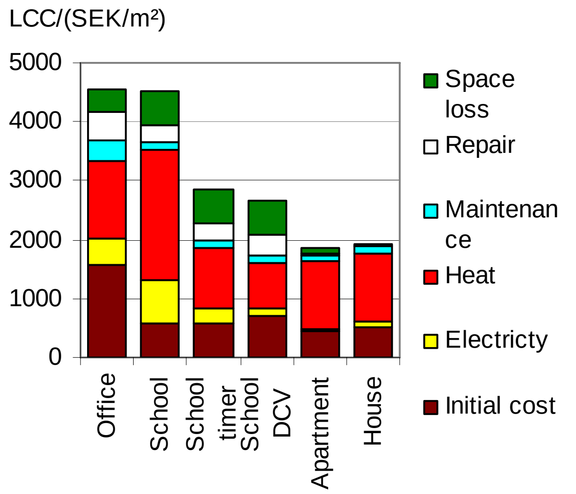

Figure 8 The life cycle cost (LCC) excluding VAT of four examples of buildings. Electricity is for cooling and ventilation. House hold electricity is not included. Initial cost occurs at the erection of the building. The rest of the costs occur during the rest of the life cycle. 1 SEK ≈ 0.14 USD ≈ 0.11 EMU 2007-02-15.

The office example was set up to use a supply and exhaust ventilation system with constant airflow rate in combination with passive beams for support cooling and hydronic radiators for support heating. The total floor area was 1080 m². In the base case, the school, with a total floor area of 1200 m², had a supply and exhaust system with constant airflow rate. The benefit from a timer decreasing the off-time airflow rate and occupancy controlled ventilation (DCV) is shown respectively for comparison. The multi-family apartment building with 2080m² and the detached house with 192 m² were supposed to have a constant airflow rate exhaust ventilation system, hydronic radiators and no cooling. The outdoor climate was taken from Stockholm, Sweden. More detailed input data is given by Johansson (2005).

Other results are:

- Heat recovery is always profitable. The ratio between saved power and added electricity due to added pressure loss of the heat recovery unit is approximately the exhaust air temperature minus the outdoor temperature in °C or K. For average Swedish outdoor climates, this means in the magnitude of 15.

- Since the initial cost is a significant part of the life cycle cost both for parts of the indoor climate system and for the whole, the life cycle cost optimisation is a blunt tool for decreasing the energy use in the built environment.
- If work productivity, sick leave, health and comfort are influenced according to recent studies, it can have a large impact on the life cycle cost.

DISCUSSION AND CONCLUSION

When new building regulations, various requirements from the client and the EU directive of energy performance of buildings is incorporated to the building sector, more care has to be taken regarding both life cycle costs and energy use. The presented model will be helpful for calculations as well as understanding the life cycle cost for indoor climate systems, which can be helpful for developing indoor climate system components. The example in the results shows that more expensive systems from an initial perspective can sometimes decrease the life cycle cost and the energy use.

Future research could provide a model that includes the entire building in the life cycle cost. More knowledge is needed regarding how to build good, inexpensive, sustainable and easy to use indoor climate systems in energy efficient buildings, in particular dwellings.

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