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A SOFTWARE APPROACH FOR ECONOMIC OPTIMISATION OF ENERGY USE IN BUILDINGS

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SYNOPSIS
When designing a new, or retrofitting an existing building it is desirable to minimise the heating/cooling load, total energy use and emissions from combustion. Solutions to accomplish this has to be held up against investment costs, maintenance costs, longevity and of course indoor climate (among other things). Optimisation between these different and often competing criteria is complex, and involves a lot of parameters. In real life such an optimisation process is often done in a superficial way, or designers often use well-known climatization solutions without evaluating alternatives.

Energy in Buildings 2.0 (EiB) is a very user-friendly Windows application, applying the graphical user interface possibilities in Windows 3.1/Windows95. It simulates temperature, power demand, energy use and emission release from combustion. It is also possible to do profitability analysis of measurements/alternatives. *EiB* can be used in design of new buildings or retrofitting of existing buildings.

Simulations in this paper shows that smart energy design in commercial buildings , often using building dynamics, can reduce the energy consumption dramatically. Measures like : daylight utilisation, use of thermal mass, hybrid ventilation systems and demand controlled heating, ventilation and cooling, are very effective for reducing the energy use in commercial buildings. Profitability analysis indicate that many of these energy efficiency measures are cost effective.

1 Introduction

Optimisation between competing criteria (e.g. indoor climate and energy use) when designing the climatization concept of a building, can be done by profitability analysis, comparing discounted running costs (salary, energy cost, maintenance cost, etc.) with investment costs. This is possible providing you have a model (or models) that can predict heating and cooling load, total energy use and thermal comfort. In order to do such model predictions in reasonable time with necessary accuracy a computer program has to be used, which take into account all the essential factors like : Insulation level of the building fabric, fabric tightness, internal loads, occupant behaviour, solar gain, thermal storage capacity, ventilation system solutions, energy generation plant efficiency, distribution systems, operating times, etc.

Experience shows that such computer programs has to be very user-friendly to be used by designers. Too many complex computer tools have been developed, only to be used by a few researchers for academic purposes.

Energy in Buildings 2.0 (EiB) is a very user-friendly Windows application, applying the graphical user interface possibilities in Windows 3.1/Windows95. It simulates temperature, power demand, energy use and emission release from combustion. It is also possible to do profitability analysis of measurements/alternatives. *EiB* can be used in design of new buildings or retrofitting of existing buildings.

EiB has been widely used in Norway for three years. From user feedback a more versatile, accurate and user-friendly version 2.0 has been developed. Based on a dynamic simulation (hour by hour calculation), more accurate prediction of cooling load, solar gain, ventilation plant and use of thermal storage (passive solutions) has been possible.

The program is element based, that is. you can describe as many ventilation plants, facades, windows, internal loads and energy plants as desirable. This gives a very flexible program which can simulate a wide variety of buildings, from simple residentials to large complex commercial buildings.

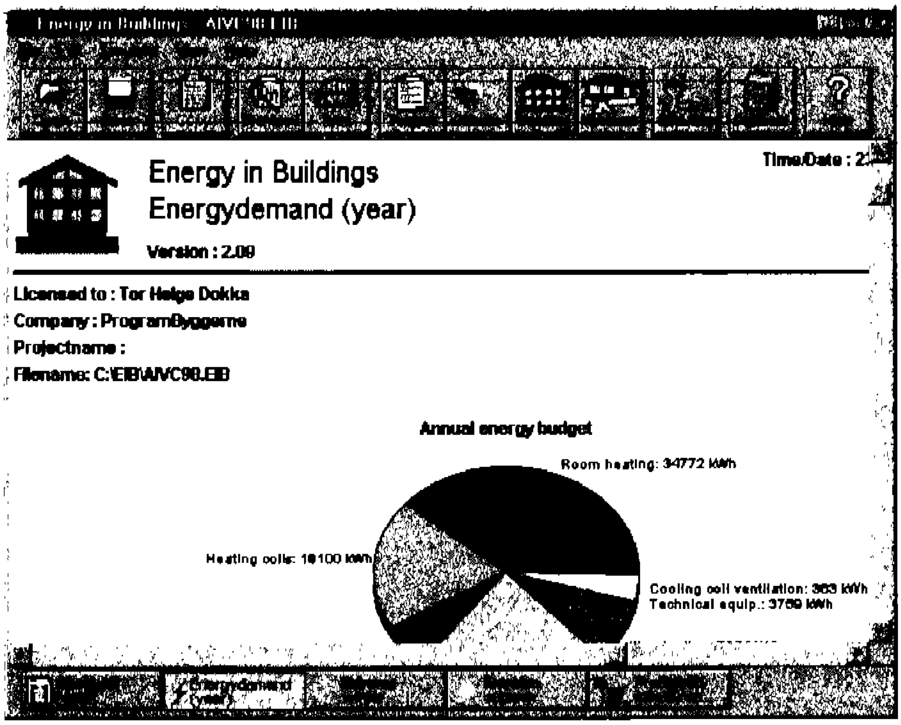

Figure 1 : The user interface in EiB

2 Models

EiB consist of several integrated submodels where the most important is the thermal model. The most significant models in *EiB* is given a description below.

2.1 Thermal model

This is the main "engine" in *EiB*. The simulation of temperature, cooling and heating load on a hourly basis (one hour timestep) is based on a one mass model. This means that all the internal effective heat capacity of a building is "concentrated" in a single mass with the same temperature.

All loads (heat gains, external temperature, solar gains, etc.) is approximated as step-functions (constant during the timestep of one hour). This makes it possible to solve the governing differential equation (from the heat balance) analytically. This analytic expression is used to calculate indoor temperature, and evaluate heating and cooling load to keep a desired setpoint temperature.

2.2 Ventilation and infiltration models

The ventilation model for balanced ventilation is based on submodels for heat exchanger, heating coil, cooling coil and fans. Output from the heat exchanger to the supply air is calculated from the exchangers temperature efficiency. The heat exchanger and heating coil is assumed regulated in sequence, that is : the exchanger delivers its maximum capacity before the heating coil kicks inn. The exchanger can be regulated to a desired setpoint temperature or be non-regulated. The heating coil is regulated after a desired setpoint temperature, and it is assumed that the coil has sufficient capacity to reach this temperature. The cooling coil is also regulated after a desired setpoint temperature, and has sufficient cooling capacity to reach this temperature. If the dewpoint temperature in the supply air dips below the apparatus dewpoint (ADP) of the cooling coil, the necessary cooling capacity to remove the latent heat of evaporation is calculated and added to the "dry" cooling load. The ADP temperature is calculated from the user given efficiency (contact-factor) of the cooling coil. Placements of fans can be either before or after the heat exchanger. The fans are described with a constant temperature rise of the supply and extract air. Its possible to describe multiple ventilation system in the same building(or energy zone).

Infiltration is either described with a user given constant air change per hour (ACH), or calculated with the Lawrence Berkley Laboratory (LBL) model. In the LBL model the infiltration air exchange is calculated from temperature difference inside/outside (stackeffect), the buildings stackheight, wind speed, shielding from terrain, distribution of air leakage, total building tightness and unbalance in the mechanical ventilation system. Air exchange in naturally ventilated buildings with evenly distributed openings can also be estimated with the LBL-model.

2.3 Window and solar model

Heat loss through windows is calculated using the total U-value for the window. Solar heat gain through windows is based on an algorithm which take into account :

- Reduction in solar intensity through panes, described by the total solar heat gain coefficient (direct and secondary heat gain). A semi-empirical formula that estimates the reduction in solar gain with increased incident angle is also implemented
- Reduction in solar gain due to artificial solar shading devices is calculated with a solar shading coefficient
- Geometric models for shading from overhangs, fins, nearby buildings and the horizon is implemented. Shading is calculated on a hourly basis from the sun position in the sky
- Solar flux on facades is calculated from solar altitude, azimuth angle, wall orientation and inclination, atmospheric transmissivity and ground reflection. Solar altitude and azimuth is calculated from time of year, time of day, latitude, longitude and timezone of the location. On cloudy days solar flux reduction (compared to sunny days) is calculated by the cloud cover factor (0-1), and division of direct and diffuse radiation is calculated from the cloud cover index. The solar model is mostly taken from Kimura, \2\ and Duffie&Beckman, \3\.

2.4 Simulation of monthly and annual heating and cooling load
To avoid large hour by hour climate files, a simplified climate and energy simulation model has been developed. Each month is first split into typical sunny days and typical cloudy days. Temperature data for these two days has to be given for each month; mean temperature and temperature amplitude (assumed a sinusoidal variation). The number of sunny days each month must also be known/estimated. Four days each month is simulated : A sunny day with normal operation schedule, a sunny day with weekend/holiday operation schedule, a cloudy day with normal operation schedule and a cloudy day with weekend/holiday operation schedule. Each day is simulated several times to reach diurnal stabile conditions. The temperature, heating and cooling load the last day is recorded. To get the monthly heating and cooling loads the four days are weighted according to the number of sunny and cloudy days and the number of normal operational days and non operational days each month. Annual heating and cooling load is of course the sum of the monthly loads.

2.5 Calculation of energy use, energy costs and emissions
The calculated heating and cooling load is the internal demand of the building, and can be quite different from the total energy consumption of the building. This is due to the efficiency of fuel burning devices, loss in distribution system, and coefficient of performance of cooling machines and eventual heat pumps. In *EiB* different models to account for this is implemented.

Heating
Different energy sources (e.g. heat pump and electric heating) can meet the demand for room heating. Each energy source has to be given a maximum heating capacity and efficiency or COP. The heating load for the heating coil and the tap water, is assumed covered by one of the described energy sources for room heating.

Cooling
The electric energy use for the local cooling system (e.g. chilled ceiling) and cooling coil(s) is calculated from the given COP for the cooling system. It is possible to have multiple local cooling systems and cooling coils with different COP values.

Energy costs
Energy costs for the building are calculated from the gross energy use and energy price per kWh for the different energy sources. Electricity is possible to describe with a seasonal varying tariff, while the other energy sources is given a constant energy price.

Emissions
Emission of CO_2, SO_2, NOx and particles is calculated from the gross energy use for each energy source. Both local generated emissions from fuel burning devices in the building and emissions from energy plants delivering electricity or district heating are taken into account.

2.6 Energy efficiency measurements and profitability analysis
To estimate the profitability of measurements on existing buildings or evaluating different design alternatives on new buildings, an economic profitability model has been implemented in *EiB*. Elements from the existing building is replaced by new elements (e.g. new windows, more efficient ventilation, more efficient boiler, etc.). An

annual simulation for both the existing and "new" building are done, and the difference in energy costs are calculated. This difference, that is the annual saved amount, is used to calculate present value, present value quotient, internal rate of return and payback period. Investment, lifetime and increase/reduction in running and maintenance costs for each measure has to be given.

3 Case : Optimisation of energy use in a new office building

To illustrate the use of *EiB*, a new office building in Oslo have been simulated with different design alternatives. All design alternatives comply to the new Norwegian building code (of 1997).

3.1 Demands in the Norwegian building code

The Norwegian building code sets an upper limit for the U-value for walls, floor. roof and windows. The upper limit for commercial buildings are given in table 1.

Table1 : Upper limit for the U-value in the Norwegian building code

	Wall	Floor	Roof	Windows
U-value (W/m^2K)	0.22	0.15	0.15	2.0

Demands for ventilation rates are : 7 l/s per person, and in addition 0.7 l/s per square meter floor area when low emitting building materials is used, 1.0 l/s m^2 where building materials with normal emission is used and 2.0 l/s m^2 when building materials with undocumented emissions is used.

Alternative 1 : ordinary design

A three storey building is located in Oslo. In the ordinary design, alternative 1, it has the following data :

- Heated floor area and air volume : 2100 m^2 and 6300 m^3
- U-values for walls, windows, floor and roof is complying the Norwegian building code (0.22, 1.6, 0.15, 0.15).
- The total window area is 20 % of the floor area (30 % facing South, 30 % facing North, and 40 % East and West)
- Balanced ventilation with cooling coil, heating coil and heat exchanger : 3.33 l/s m^2 in normal operation schedule (12 hours a day) and 1.67 l/s m^2 outside normal operation (night and weekends). Specific fan power : 3 $kW/m^3/s$. Heat exchanger efficiency. : 50 %. Supply temperature : 18 °C (constant).
- Internal loads : Lighting 14 W/m^2 (10 hours a day), Equipment 10 W/m^2 (8 hours a day). On average 150 occupants per day 8 hours a day.
- Heating : Radiators with setpoint temperature 22 °C. Efficiency heating : 100 %.
- Cooling system : Chilled ceilings with setpoint temperature 22 °C. COP cooling system : 2.0.
- Operation : 5 days week, with Christmas and Easter vacation. Normal operation in summer months.

This is a rather usual design of an office building in Norway, where no special effort has been done to design the building energy efficiently, besides complying with the building code. The annual net energy use for this building is simulated to 292 kWh per square meter floor area. The annual energy budget is given in table 2.

Alternative 2 : Energy efficient design
In this design more energy efficient ventilation and night setback is implemented to reduce energy use :

- Use of rotating wheel heat exchanger with a temperature efficiency of 70 %
- Low pressure design of ventilation system with a reduction in specific fan power to 2 $kW/m^3/s$
- Use of building materials with normal emission, reducing the ventilation demand to 2.77 l/sm^2
- More seasonal adapted supply temperature, 19 °C in winter months and 17 °C in summer months
- Night setback of the heating system to 17 °C, 8 hours each night and in weekends.

With this design the net energy use is reduced to 210 kWh/year m^2.

Alternative 3 : Optimum energy design
The third alternative is an energy optimised design, with the following measures :

- Low pressure hybrid ventilation system , with specific fan power of : SFP = 1.0 $kW/m^3/s$. Heating coil is removed. Use of cooling coil with a COP = 3.0
- Low pressure heat exchanger with temperature efficiency of 60 %
- Use of low emitting building materials, and demand controlled ventilation, reduce the ventilation rate to 1.94 l/sm^2, 10 hours a day. Reduces to half the air flow outside normal operation schedule.
- Use of energy efficient lighting with daylight utilisation : 5 W/m^2, 9 hours a day
- Use of energy efficient equipment (computers and printers) : 4 W/m^2, 8 hours a day
- Removal of the local cooling system (chilled ceiling). Acoustic ceilings are removed and flooring material with small heat resistance are used to "expose" the concrete floors. This utilisation of thermal mass reduce cooling demand and overheating in the summer.
- Use of a heat pump system for room heating and tap water heating, with a COP = 3.0. Peak heating load is covered by an electric boiler.

With these measures the net annual energy use is reduced to 113 kWh/m^2. This is the net (internal) energy demand. The gross demand (energy delivered to the building), taking account the COP of the heatpump system, is down to the low value of 57 kWh/m^2yr

Table 2 : The net energy budget for the three design alternatives

Annual net energy budget	*Ordinary*	*Energy eff.*	*Energy optimised*
1. Room heating	65	30	63
2. Heating coils	64	41	0
3. Water heating	12	12	12
4. Fans/pumps	54	33	11
5. Lighting	45	45	15
6. Equipment	27	27	11
7. Room cooling	20	17	0
8. Cooling coils	6	5	1
Sum item 1-8	**292**	**210**	**113**

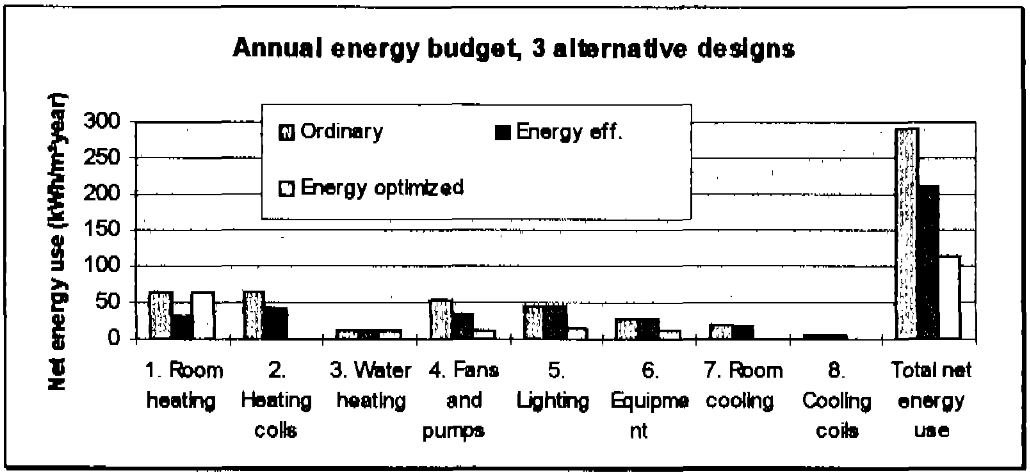

Figure 2 : Net energy budget for the three design alternatives

Profitability

It's obvious that measures in alternative 3 reduce the energy use considerable, but is this measures profitable for the building owner? To answer this question a profitability analysis has to be undertaken.

The measures in alternative 3 are merged into three measures :

Measure one : New hybrid ventilation system, and use of low emitting building materials. The measure reduce the duct and air handling unit costs with approximately 11 000 Euro (99 000 NOK). The costs for more expensive control system and heat exchanger (run around type) is estimated to 15 000 Euro (135 000 NOK). Extra costs in the building fabric due to the hybrid system is estimated to 12 000 Euro (108 000 NOK). The net investment costs compared to the ordinary design is then 16 000 Euro (256 000 NOK). Maintenance cost is assumed to be the same as with the balanced system, and the economic lifetime is set to 15 years.

Measure two : Use of energy efficient lighting and equipment. The daylight utilisation control system is estimated to 23 000 Euro (207 000 NOK). The extra cost for more energy efficient computers, monitors and printers is calculated to 60 000 Euro (540 000 NOK). Maintenance costs is the same as for ordinary design, and economic lifetime is set to 5 years.

Measure three : Use of heat pump system and removal of local cooling system. The reduction in cost of removing the local cooling system is 30 000 Euro (270 000 NOK). Installation of the heat pump system is estimated to 75 000 Euro (675 000 NOK). Maintenance cost for the removed cooling costs and the increased costs for the heat pump system is calculated to be the same. Economic lifetime is set to 15 years.

The interest rate for all measures are set to 4 %, and the electric energy price is 0.055 Euro/kWh (0.5 NOK/kWh).

Table 2 :Profitability of energy efficiency measures, alternative 3.

Energy Efficiency Measures	*Present value (Euro)*	*Present value quot. (-)*	*Internal rate (%)*	*Payback period (years)*	*Energy savings (kWh/yr)*	*Saved amount (Euro/yr)*
Hybrid ventilation	138 424	9.65	86.7	1.2	24 8019	13 889
Heatpump + no local cooling	57 617	2.28	19.0	5.5	16 4813	9 230
Reduced internal loads	-62 575	0.25	-31.8	32.8	8 1927	4 588
Sum measures	133 466	1.93	13	5.9	49 4759	27 707

4.0 Discussion, conclusions and further work

- There is a big demand for user friendly simulation programs that evaluate different designs to get energy efficient and environmental friendly buildings
- Programs has to be designed with the practical designers needs in mind
- Simulations shows that other measures than better insulation and high efficiency heat exchangers can be effective in reducing the energy use in commercial buildings
- Simulations and profitability analysis indicate that measures like : daylight utilisation, use of thermal mass, hybrid ventilation and demand controlled heating, ventilation and cooling, is cost effective.
- To be used extensively, designers also has to be sure that these programs produce accurate results. It is therefore very important to validate the models in the best possible manner. *EiB* is soon to be tested against the BESTETST procedure, \4\. This validation procedure will be published in a later paper.

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