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Global Energy Cost of Building Construction and Operation

Analyse énergétique de la construction et utilisation de bâtiments

Energieaufwand für Erstellung und Betrieb von Gebäuden

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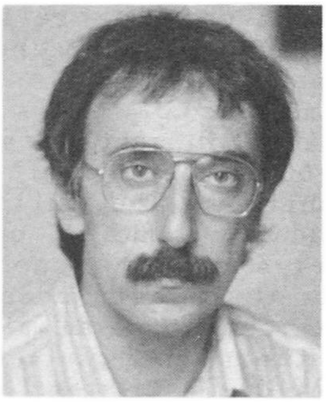

Niklaus Kohler was born in 1941 and graduated as an architect from the Swiss Federal Institute of Technology (EPFL), Lausanne, where he also got his Ph. D. He worked in Research and Development in the building industry before joining the Research Group on Solar Energy of the Physics Department of the EPFL.

SUMMARY

The amount of energy used for the production of building materials, building construction, repairs, operation and demolition is determined. A parameter study indicates the predominance of direct energy costs (heating and warm water) for current buildings. For low energy buildings the part of indirect (construction) energy becomes important. The feasibility of several optimization strategies is discussed.

RÉSUMÉ

Les besoins en énergie primaire pour la production de matériaux de construction, pour la construction, l'entretien, l'utilisation pendant la durée de vie et la démolition de maisons typiques ont été calculés. Une étude paramétrique montre la prédominance des coûts énergétiques directs (chauffage) pour les maisons actuelles. Pour des maisons à basse consommation d'énergie, les coûts énergétiques indirects deviennent un facteur important. L'efficacité de plusieurs stratégies d'optimisation est discutée.

ZUSAMMENFASSUNG

Der Primärenergiebedarf für Baumaterialherstellung, Erstellung, Unterhalt, Betrieb während der Lebensdauer sowie Abbruch wird berechnet. Eine Parameterstudie zeigt die überwiegende Bedeutung der direkten Energiekosten (Heizung) für durchschnittliche heutige Gebäude. Bei Niedrigenergiehäusern wird der Anteil der indirekten Energiekosten ein wichtiger Faktor. Die Wirksamkeit verschiedener Optimierungsstrategien wird diskutiert.

1. INTRODUCTION

Since the first so called energy crisis several new problems have appeared:

- the limits of natural resources have become apparent
- pollution has begun to affect irreversibly the environment
- all countries, developed or not, depend on the continuous availability of cheap energy.

The traditional techniques of environmental planning, particularly planning of buildings have to be revised. New planning tools and additional optimization criteria are needed. The life-cycle-cost approach is such a planning tool.
Building as a whole is one of the most energy intensive activities. Energy consumption for space heating and warm water preparation accounts for 30-50 percent of the overall energy consumption in industrialized countries. The building industry, above all the building material industry absorbs probably the largest part of energy of all industries and the energy consumption per value is relatively high. In the last decade the principal building material producers (cement, aluminium, brick, etc.) have considerably reduced their energy consumption per unit. The most efficient technologies dominate the market. The energy needs for most materials are known today. At the same time the research on the energy consumption patterns of buildings has progressed. Today it is possible to establish the overall needs for building from material production through heating during life time to demolition. A survey of the literature on the subject shows, however, large differences in the estimated overall energy costs resulting from different methodological approaches.

2. ENERGY ANALYSIS

The aim of all energy analysis is to answer the question : How much energy is used to manufacture a product or how much energy a process needs? The first question relates to the so called "energy costs" (in this publication given as as kWh) resulting from a product oriented approach. The second question which requires the analysis of a process is a more sectorial approach. To establish life time energy costs of buildings requires the combined use of both methods.

The fundamental principle of energy analysis is that for a given product or process the total energy content is equal to the total energy input. The energy can take several forms.

- -direct energy in the form of fuel, electricity, gas;
- -indirect energy necessary for the production of fuel (energy costs of fuel);
- -indirect energy embodied in materials and components.

The main problem of energy analysis is the delimitation of system boundaries. There is no correct or absolute value for energy needed to produce a kilogram of any commodity. The values obtained depend critically upon the system boundaries chosen. (1)

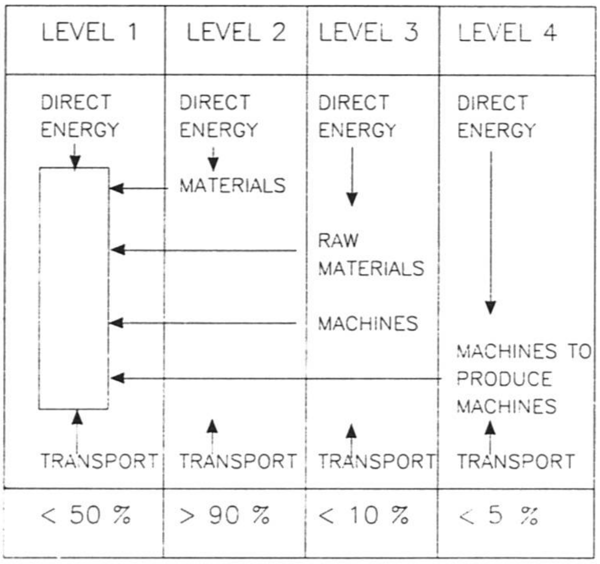

Fig.1: The energy and material flow and levels of disaggregation.

There are basically 3 different methods in energy analysis currently in use:

a) Processes analysis

This consists of identifying the network of process which contribute to a final product, to analyse each process and to assign an energy value to each input. There are four levels of process analysis:

1. Direct energy costs (used in the facility being considered)
2. Indirect costs embodied in the raw materials, components and in transport
3. Indirect energy costs of production equipment for 2)
4. Indirect energy costs of the equipment to produce machines for 3)

In our analysis we take into account only the two first levels which amount generally to more than 90 percent of the total energy costs. The main problems with process analysis are the difficulty in choosing the subsystems, the risks of truncatation and the lack of availability of basic data.

b) Input-output analysis

The input-output table of a national economy is a square matrix summarizing the commodities necessary to make other commodities. The entries in the table indicate the amount of commodity required as a direct input of a sector to produce a final good. The units are monetary values. The advantage of this method is that as long as we do not have a matrix in physical (energetic) terms, it is the only instrument for general observations. The method has however some important disadvantages. By looking at an entire sector there is risk for insufficient disaggregation and the impossibility to judge typical and atypical products. Leontieff divided the American economy into more than 300 sectors where as the available data for the Swiss economy distinguish less than 20 sectors. Furthermore the data depend on purely financial factors (inflation, interest rates etc.) This makes the so called "dollar energy value" a rather inaccurate unit for detailed analysis.

c) Hybrid analysis

The basic disadvantage of process analysis (truncatation) and input-output analysis (insufficient disaggregation) can be overcome by the so called hybrid analysis which combines and corrects the values found by the two other methods (2).

In our model we used the process analysis for the building structure and envelope and the hybrid analysis for building equipment, prefabrication and site work.

3. CALCULATION OF THE ENERGY COSTS OF A BUILDING

All approaches limited to the energy content of building materials or of components (walls and windows) can lead to wrong conclusions. This is why we have developed a model that takes into account the direct and indirect energy costs of the complete construction and utilisation process during the life time of a building (4). Furthermore the model combines direct and indirect costs allowing parameter studies. It is possible to analyse the influence on the total energy cost initiated by the improvement of the insulation thickness. (Less direct energy, more indirect energy).

The direct energy costs are estimated by a seasonal energy balance method which is currently used in Switzerland (3). The method takes into account the solar gains, the internal gains, the efficiency of the heating plant and the warm water production.
The indirect costs are computed from the energy cost and quantity of each building material in the analysed buildings. The feedstock energy and the possibility of recycling are taken into account for each material. The life time and replacement rate as well as the energy for demolition for each component is computed. The energy costs for prefabrication, transport and site work are calculated separately. The life time of the building is 80 years and calculations are made for an average Swiss climate.

Each building was subdivided into nine groups (structure; insulation; exterior cladding; interior finishing; openings; partition walls; heating, plumbing, ventilation; electricity and work on site) . Each group contains components with different life and repair cycles. For current buildings there are between 60 and 70 components. The possibility of recycling or combustion of materials after demolition is taken into account.

There are of course large dispersions in the basic data. Some data could be verified, others had to be taken from literature. As the origin and the calculation methods for the data were different it can be assumed that the errors compensate to a certain degree. An error analysis has been performed estimating the overall tolerances +35 percent (upper limit) and -20 percent (lower limit).

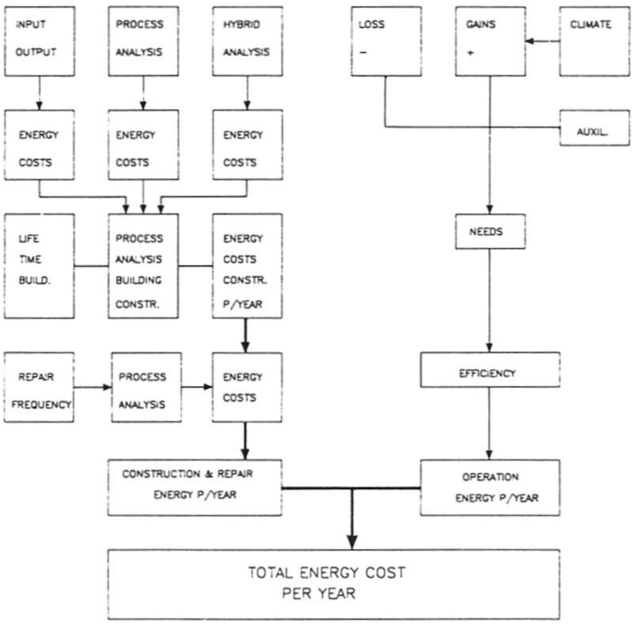

Fig. 2: Total energy costs during one year

4.PARAMETER STUDIES

28 different buildings were analysed. It is of course impossible to draw any general conclusions from such a small sample. The parameter studies can only give indications about the tendencies. The analysed buildings differed by their function (housing, single famility residences, schools, office and industrial buildings), by their main structural material (concrete, brick, steel or wood) and by their direct energy consumption (current and low energy buildings, retrofitted buildings).

a) Indirect energy costs

The indirect (construction, repair and demolition) energy costs vary from 880 kWh/m2 to 1660 kWh/m2. The average value is 1250 kWh/m2. The differences result mainly from:

- Foundations and basements (different for small and large buildings)
- Complexity
- Total mass

The distribution of indirect energy costs between the different subsystems is show in fig.3. The structural part is predominant in all types of buildings. The large part of insulation in single family residences results from the higher number of low energy houses in this group.

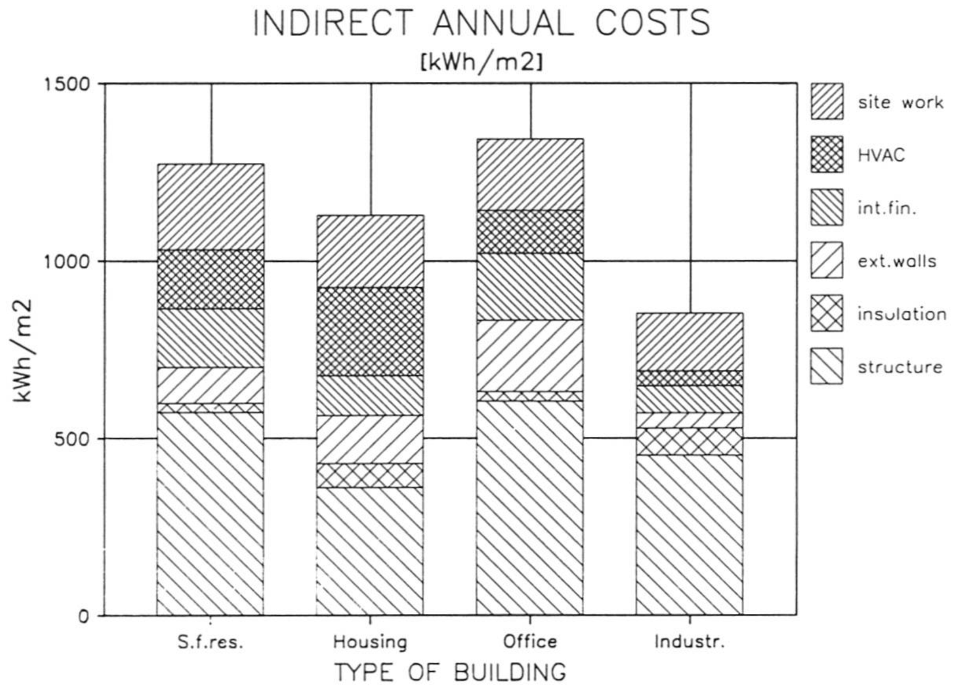

Fig.3: Indirect energy costs

b) Direct and indirect energy costs

If we want to compare direct and indirect energy costs we have to express them for a certain life time (e.g. 80 years) and use annual costs. In fig.4 the direct and indirect costs have been reported. Three groups can be identified:

-a Current Swiss buildings mostly housing with rather high mass.
-b Buildings with high direct energy costs, mostly office build ings with large air conditioning plants and bad envelopes.
-c Low energy buildings

The part of indirect energy costs in total energy costs varies from approx. 5 percent (b) to approx. 40 percent (c). The dispersion is much larger for direct than for indirect energy costs.

c) Building materials

For most building types and forms several structural materials were calculated. There were no significant differences for the overall indirect costs. The changes in coating material (e.g. from aluminium to wood) had no significant influence. These tendencies can be explained by the fact that each building is composed of many different materials and that changes of the materials in one group has no significant effect on the whole. Only the systematic changement of all energy intensive materials and the reduction of mass e.g. in replacing normal concrete slabs by prestressed TT slabs has an influence on the indirect energy costs (fig.5). It is quite clear, however, that the influence of conservation measures on the side of the direct energy costs has a much larger influence on the overall energy costs.

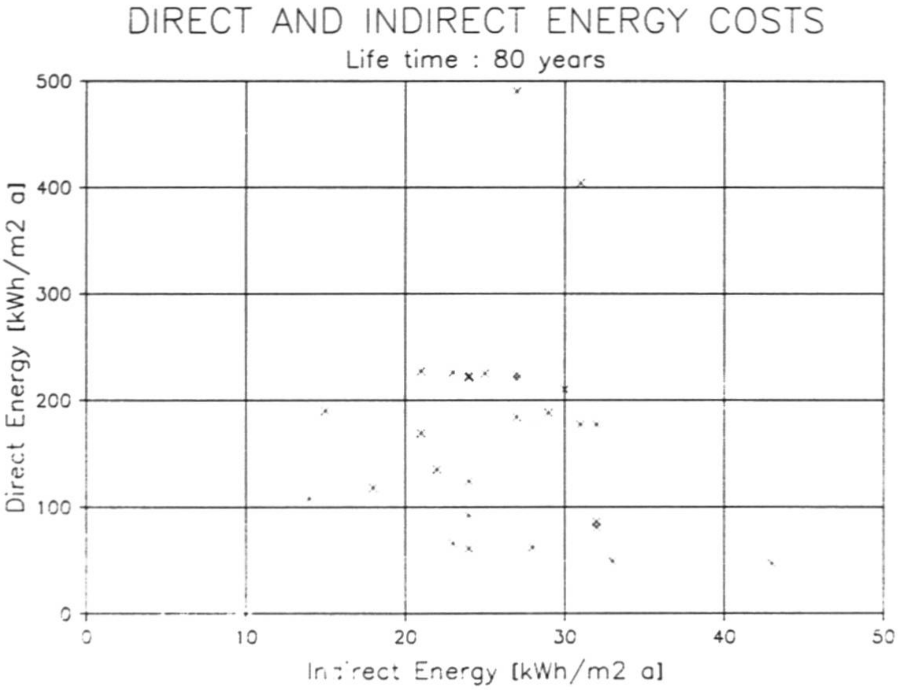

Fig.4: Direct and indirect annual energy costs (life time 80 years)

d) Retrofit measures

Some of the analysed buildings have been retrofitted. The fig 5. shows that the retrofit measures for an average housing block (upper curve) reduce the direct energy costs practically by a factor of three without raising indirect costs.

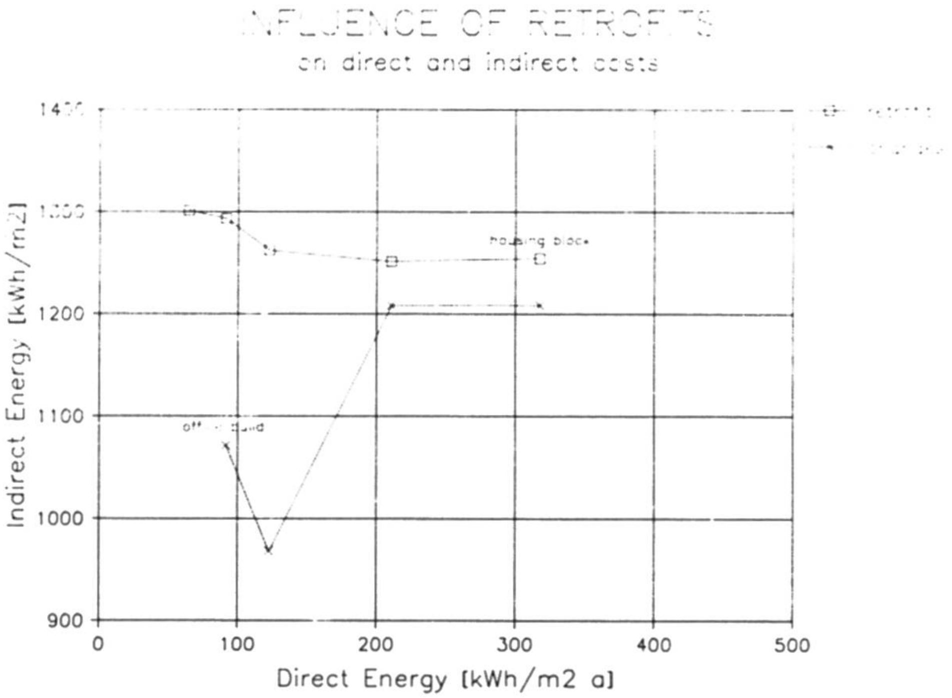

Fig.5 Influence of retrofit measures and construction technique.

The energetic payback time of the retrofit measures varies between some weeks (air tightening, control equipment) to 12 months (solar collector for warm water). The lower curve shows an office building. Retrofit measures reduce the direct energy costs. Another construction technique combined with retrofit measures reduces both direct and indirect energy costs. A supplementary retrofit with active solar equipment raises the indirect costs again.

5. OPTIMIZATION

The design process is very complex and based on many iterations, feedbacks and intuitive shortcuts. Most of the proposed optimization methods cannot be applied because the questions these methods answer never appear in the design process. All energy conservation strategies have to follow the design process as closely as possible in order to answer the right question at the right moment. Some of the optimization models are practical but they oversimplify the problem and will therefore lead to wrong conclusions. Two optimization models and an optimization procedure are presented in more detail.

a) Optimization by component

This method allows the determination of the thickness of an insulation layer in terms of energetic or financial pay back. In energetic terms this means that the optimal insulation thickness is that where the difference between the energy to produce the insulation and the possible savings in heating energy is highest.

$$d_{eo} = 1 \left(\sqrt{\frac{0.024 \cdot D \cdot T}{\lambda \cdot e \cdot \eta_c}} - R \right)$$

D=degree days
T=life time of the building
R=thermal resistance of the wall without insulation (m2.K/W)
λ=thermal conductivity of the insulation material (W/m.K)
η_c=efficiency of the heating plant
e=indirect energy cost for the insulation material (kWh/m3)

The optimal thickness follows the square root of the life time, the thermal conductibility or the efficiency of the heating plant. The same formula can be adapted to calculate the financial optimal thickness. With the actual energy prices the optimal thickness lies around 10-12 cm for most materials. The energetic optimum varies from 30 to 140 cm. These values have no practical signification.

b) Optimization of the building envelope

The envelope is composed by elements which loose energy (walls) and others which loose and gain energy (windows). Furthermore one can understand easily that it is not interesting to combine a wall

with 2 cm insulation and a high performance glass with a k value of 1.2 W/m2K.
The total energetic cost of an envelope composed of i elements (Ci) is:

$$C_I = A + \sum s_i \cdot e_i \cdot d_i + \sum s_j \cdot e_j \cdot n_j$$

A is a constant, s are surfaces, e indirect energy costs, d thickness and n the number of layers of glasses for j windows. With Ch = heating costs the total energetic cost (Ct) are:

$$C_T = C_I + C_H$$

Ct can be minimized to give an absolute minimum or with the bounded extremes method it is possible to find a minimum linked to a constant (direct or indirect energy costs). The method has been developed by Roulet (5).

The envelope comprises 10-30 percent of the total indirect energy costs of a building. This method even if it is more effective than the component optimization, adresses only part of the building.

c) Optimization procedure

The design process is very complex and generally not linear. The proposed optimization procedure gives partial answers at different design stages.

(1) Opportunity of construction
It might seem strange to answer this question but a negative answer saves by far the biggest amount of energy because it concerns the whole life time of the building. If it is possible to solve a problem by other means than constructing a new building considerable energy can be saved. Two examples: the construction of a supermarket outside a town will cause an energy consumption for automobile transportation, air conditioning, storage of refrigerated food, heating up of this food etc. which has no relation to the possible savings by using one structural material instead of another. Another example would be the decision to construct a new hospital or to treat patients in an ambulant way at home by motorized nurses and doctors. The second solution would probably consume much less energy than the construction and running of a large hospital.

(2) Transformation or demolition
The question has no general answer. Figure 6 shows the total energy consumption during 30 years for four alternatives:

Var.1: a bad existing building
Var.2: a retrofitted building
Var.3: a new low energy building
Var.4: a good old building which is retrofitted after 10 years

It is quite evident that the worst solution is the existing bad building. If the building is, however, not that bad the question of transformation and retrofit or construction of a new building has to be answerd in each case.

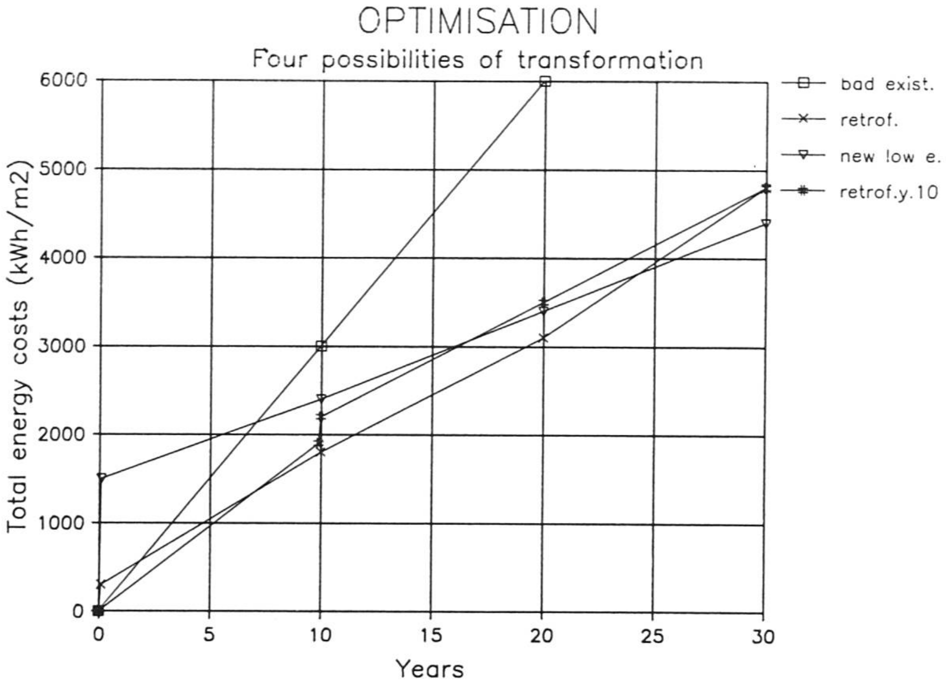

Fig.6: Possibilities of transformation or new construction

(3) Energy consumption (direct energy costs).
It is quite clear that for buildings with a life time of more than 20 years the consumption energy becomes dominant and that the main emphasis has to be put on conservation measures. Recent research shows that in Switzerland it is possible to reduce the energy consumption in housing from an average of about 220 (kWh/m2 a) to about 100 (kWh/m2 a) by current conservation methods and that passive solar buildings can be comfortably heated with even less than 100 (kWh/m2 a).

(4) Choice of building materials and construction techniques
It is possible to reduce the indirect energy costs by reducing the mass of the building, by systematically choosing materials with low indirect energy costs and preventive maintenance. Other criteria like the pollution caused by certain building materials (asbest, formaldehyde etc.) will probably become more important in the years to come. (6)

5. ENERGY ANALYSIS OF ROAD, BRIDGE AND TUNNEL CONSTRUCTIONS

The construction of roads and bridges implies only indirect energy costs. These costs will appear even in an indirect way in the financial cost. Repair intensity, demolition and life time influence the energy cost but they are relatively easy to predict because the number of different materials and components is much smaller than in a building.

The energy costs for concrete roads have been estimated to be 135 (kWh/m2) by (7). For highways with 2x2 lanes the energy costs are approximately 8 MWh/m (9).

In the construction of road tunnels two problems arise:

- the construction technique can imply large differences in the indirect energy costs. For current street tunnels and passages the energy costs vary between 15 and 26 MWh/m of tunnel (8).
For mountain tunnels estimates are approximately 17 MWh/m (9).

- the necessity for ventilation, lighting and security equipment for such tunnels implies direct energy costs. For a two-lane road tunnel (16.9 km) the annual electricity consumption is 0.936 MWh/m (9). Depending on the primary energy coefficient the indirect annual costs vary between 10 and 20 percent of the direct costs.
The data concerning the roads and tunnels are quoted from different sources. There are, unfortunately, still few research results in this field.

7. CONCLUSIONS

In the central European climate indirect energy costs amount to 7 to 15 percent of the total life time energy cost of a building. For low energy buildings this part goes up to 50 percent. In warmer climates the indirect energy costs become dominant. Overall energy costs have become an optimization criteria. The establishment of energy costs makes it possible to evaluate other impacts like pollution. In civil engineering the research on energy costs is at the beginning, there are, however, interesting perspectives in tunnel and road construction, in all kind of environment related constructions and in the the field of environment impact studies in general.

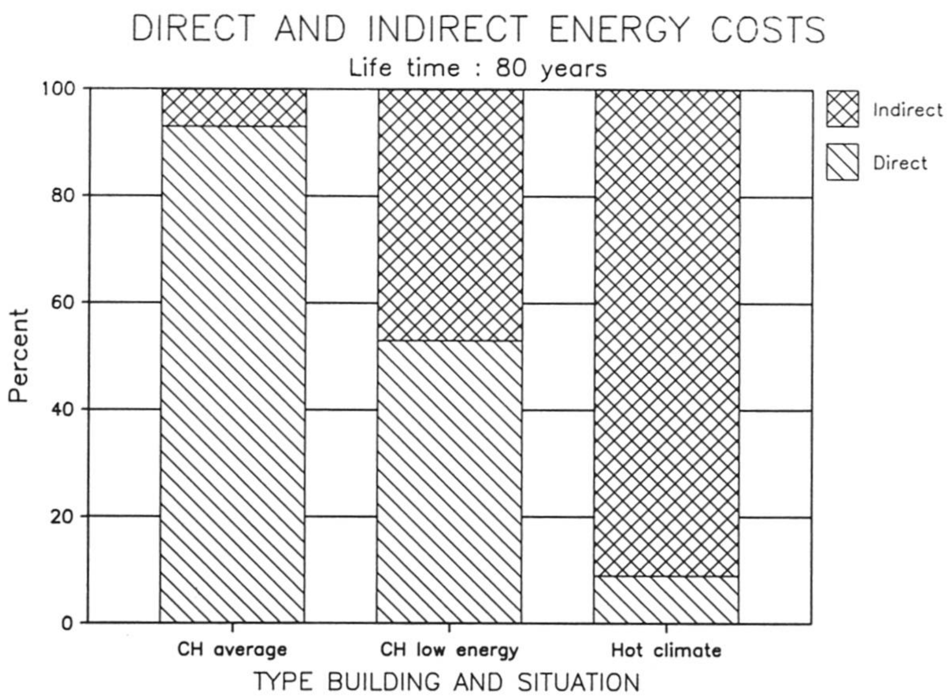

Fig.7: Direct and indirect energy costs in different situations

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