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A prototype expert system for large scale energy auditing in buildings

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1. SYNOPSIS

A demonstration prototype of an Expert Management System for Building Energy Auditing has been set up, which will require international cooperation for its further development. It incorporates sophisticated algorithms, such as a Neural Network Pattern Associator, for rapid identification of the Energy Conservation Opportunities most likely to be suitable for the building under audit.

2. ABSTRACT

A prototype expert system, named BEAMES (Building Energy Auditing Management Expert System) has been developed at the European Communities' Joint Research Centre (JRC). This is intended to be the first step in the development of a knowledge-based tool for improving current auditing techniques. The need for such a tool derives from the fact that it is very difficult for auditors, no matter how expert they may be, to master the huge amount of knowledge required e.g. audit techniques and procedures, prices, calculation models, norms and standards, and so on. The availability of a guided audit on a portable PC would not only assist in the execution of a complete audit but also provide an excellent training tool for new professionals in the field. The audit scheme used is based on the recommendations of the IEA Annexe XI on Energy Auditing in Buildings. The expert system is based on a Neural Network Pattern Associator (NNPA) which derives a set of Energy Conservation Options (ECOs) that, according to previous experience of auditing similar buildings, is very likely to be applicable to the case under investigation. Additional likely ECOs are identified on the basis of simple information requested from the building owners or administrators. The auditor is then guided in the detailed audit phase by means of specific data requests associated with each selected ECO. The program indicates the audit procedures and measurement techniques needed for gathering the data required. A final report is compiled according to the identified ECO list and to the economic assessment of the ECOs.

3. INTRODUCTION

3.1 Background

Buildings are attracting increasing attention from policy makers, public administrators and industrialists. With more than 150 million existing dwellings and a large number of very heterogeneous tertiary buildings, renovation is likely to become an important industrial and economic issue for the European Community, from the energetic, environmental, urban and social points of view.

In fact,

- the building sector is that in which the highest energy consumption and waste occur and it will be the target of many energy conservation (Demand Side Management) actions;
- problems of mobility and pollution are strictly related to existing urban layout, which is rapidly becoming inadequate for modern living and working conditions and technologies
- due to the very long lifetime of buildings, poorly performing constructions produce negative impacts for many decades, making the solving of the energy and environment problems more difficult;
- in Europe, the availability of land is limited and more stringent environmental constraints will be raised against new constructions

- social integration and the prevention of ghettos should also lead to building renovation as a means of avoiding major social protests or riots,
- a vast patrimony of historic buildings has to be restored, to conserve European national identities.

For all these reasons, it is probable that, in external appearance, towns of the next century will not be very different from today's. The building industry will be obliged to shift more of its activities towards the renovation of old buildings, whilst the rate of new constructions is likely to decrease. Technical improvements will probably occur more frequently in the fields of HVAC equipment, home and office appliances, and building energy and service management. However, implementation, in a new construction, of the best available techniques today will not avoid the need for retrofits in 20 or 30 years, due in particular to the rapid obsolescence of informatic control devices and of many building and plant components. On the other hand, speeding up the commercialisation of prototype technologies can bring rapid improvements to energy consumption levels. The setting up of advanced techniques of building retrofit is, therefore, something that will become more urgent as time passes. Among these tools those required for carrying out careful and effective Energy Auditing (EA) are of particular importance.

Building energy auditing is a fundamental part of any retrofit action on buildings, from the energy, environmental, maintenance, safety, structural reliability and legal certification points of view. The Commission of the European Communities has prepared various Draft Directives for the EC Council of Ministers in the field of Building Energy Certification, in order to save energy, reduce CO₂ emissions, and make the real estate market more transparent. Norms and schemes for Building Energy Labelling are being introduced in many European countries. Denmark anticipated the CEC Directive in 1986, making Energy Auditing mandatory in all real estate transactions. France has the largest experience of EA schemes since 1980 and several Energy Labelling schemes have been launched in the UK with official backing, after the positive experience of the Energy Cost Index, tried out at Milton Keynes. Following norm n.10 of Jan.9, 1991, Energy Certification procedures are also being implemented in Italy. In Portugal, the Ministry of Public Works intends to propose systematic EAs in residential and tertiary buildings.

These requirements have led scientific organisations to become interested in the development of sophisticated design tools both for new buildings and for retrofit actions on existing buildings. Today, the trend, on the one hand, is to develop and translate the most practical aspect of building science and related norms into software for use on Personal Computers or Microcomputer stations. On the other hand, it is to improve modelling techniques (particularly in those areas such as lighting and daylighting, which received less attention in the past) and their integration or interfacing with other models or information systems. For instance, the interfacing of thermal calculation models with CAD packages and with Energy and Architectural Data Bases can provide very effective and powerful assistance to building architects and energy designers.

3.2. Scope

The need for an expert system in the Energy Auditing area was highlighted by a study (G. Helcke' et al. 1987) in which a benchmark comparison of commercial energy auditing methods showed that little agreement existed between the recommendations and no correlation between the cost and accuracy of various commercial audits. The need for standard methodologies in the field of building auditing, together with the development and use of common European norms and standards was made apparent. Moreover, the JRC participated in the activity of the IEA's Task XI on Energy Auditing, the final product of which was a 2 volume Source Book published in 1987. In this work, between 200 and 300, often interacting, Energy Conservation Opportunities (ECOs) were described, together with different implementation strategies according to specific situations. This work has been continued at the JRC where other ECOs, derived from the most recent applications of bioclimatic architecture have been added to the list. It soon became evident that the links and interconnections among ECOs, analysis and measurement techniques and audit procedures could only be fully mastered by loading and managing the knowledge on a computer. During 1990, it was, therefore, decided to develop an energy management expert system aimed at improving the auditing of existing buildings. This informatic tool, (a skeletal, demonstration version, restricted to residential buildings, is presented here), can give an impressive idea of how advanced

mathematical algorithms and recent advances in Artificial Intelligence can find practical application and provide greatly enhanced auditing techniques.

This product is mainly addressed to:

- the large number of **professionals** (engineers, architects, technicians) who will be responsible for building energy certification, an increasingly important requirement for building and/or urban area retrofit actions
- large **public or private building owners**.
- **building energy saving companies** and the **energy utilities** involved in Demand Side Management programs.

The tool is intended more as a support and field-guide than an office assessment package. For this reason it has been designed to run on a standard portable PC (under Windows environment). Portable computers with built-in CD-ROM for interactive multimedia information tools will become available within a few years, by which time this tool could be ready for use.

The basic reasons for the development of this new tool are the following:

1) The need to master all the existing knowledge in the field.

The expertise required for an energy audit ranges from the analysis of the performance of different building functional categories and various types of heating, cooling and electrical systems, to the detailed knowledge of possible energy conservation opportunities (ECOs). Norms, standards, rules and regulations, safety criteria and costs, measurements and analysis techniques, all have to be borne in mind and optimum decisions taken quickly and efficiently. It is clearly almost impossible for professionals, no matter how expert they may be, to master all this knowledge efficiently.

2) To ensure the reliability and completeness of the audits

As the JRC benchmark experiment demonstrated (G. Helcke' et al,1987), commercial audits provide different recommendations depending on the scheme used, on auditor training, on ECO implementation strategies, and on national norms, etc.

3) To improve the audit cost-effectiveness

Tariffs for audits are fixed in those European countries where building energy audits are required for Building Energy Certification or Labelling procedures, as required by the European Directives. However, the audit quality could be greatly enhanced if more care were to be devoted to field measurements and less time to pre-audits and the compiling of reports

4) The need to train new auditors.

If extended retrofit actions have to be launched in many European towns, this will imply the training of several hundreds of auditors. The availability of a tool which can guide and improve the operational activity of new auditors would be a very useful aid.

Last but not least,

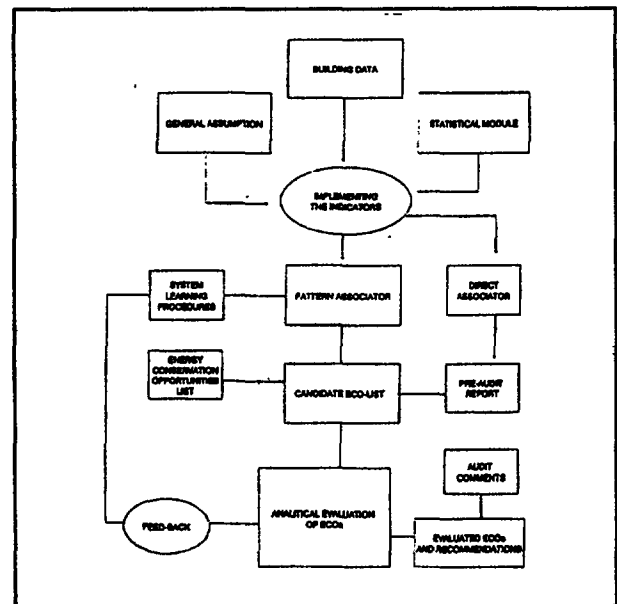


Figure 1.

5) Common tool for the Single European market

This package can include **European norms and standards**, **calculation procedures**, and the most recent technical information in the field of energy savings and renewable energy applications in buildings. Such a package would assist Single Market integration.

4. DESCRIPTION OF BEAMES

4.1 Main performance features of BEAMES

BEAMES is a demonstration program aimed at the development of knowledge-based software for energy auditing in buildings. The word "audit" is to be understood as the identification not only of the building energy flows but also of the Energy Conservation Opportunities (ECOs), including energy maintenance requirements. The program represents a substantial improvement with respect to existing auditing methods, since it makes it possible to identify the most likely candidate ECOs for retrofit measures already at the preliminary phase .

Conventional building energy auditing schemes usually make use of a rather large amount of thermo-physical and geometrical data in order to be able to identify, by means of simulation, the energy flows, consumption levels and savings potential. This information is not, however, easily available from building owners and managers. Moreover, this approach does not provide any indication of the likely ECO set nor of the type of audit measurements which will be required during the site visit. The auditor cannot, therefore, properly plan the visit beforehand or evaluate its cost and be sure of the completeness of the audit.

The BEAMES program utilises an "expert management system" which acts rather like a human expert. It is formed by different functional modules or "objects" linked into the model logic structure (Figure 1). In the early audit phase only a small amount of information, of the type which can be provided by non-technical people (such as the building owner or administrator) is gathered (Figure 2). BEAMES then develops

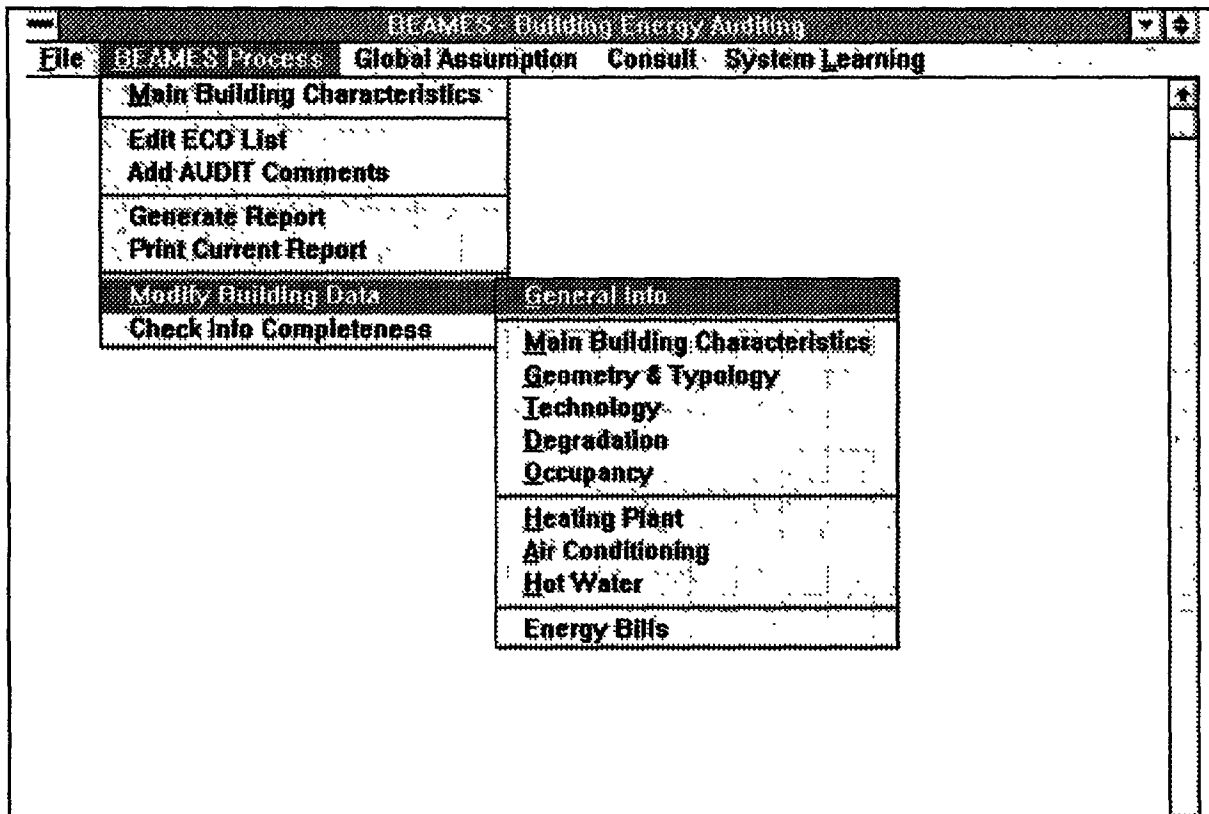


Figure 2.

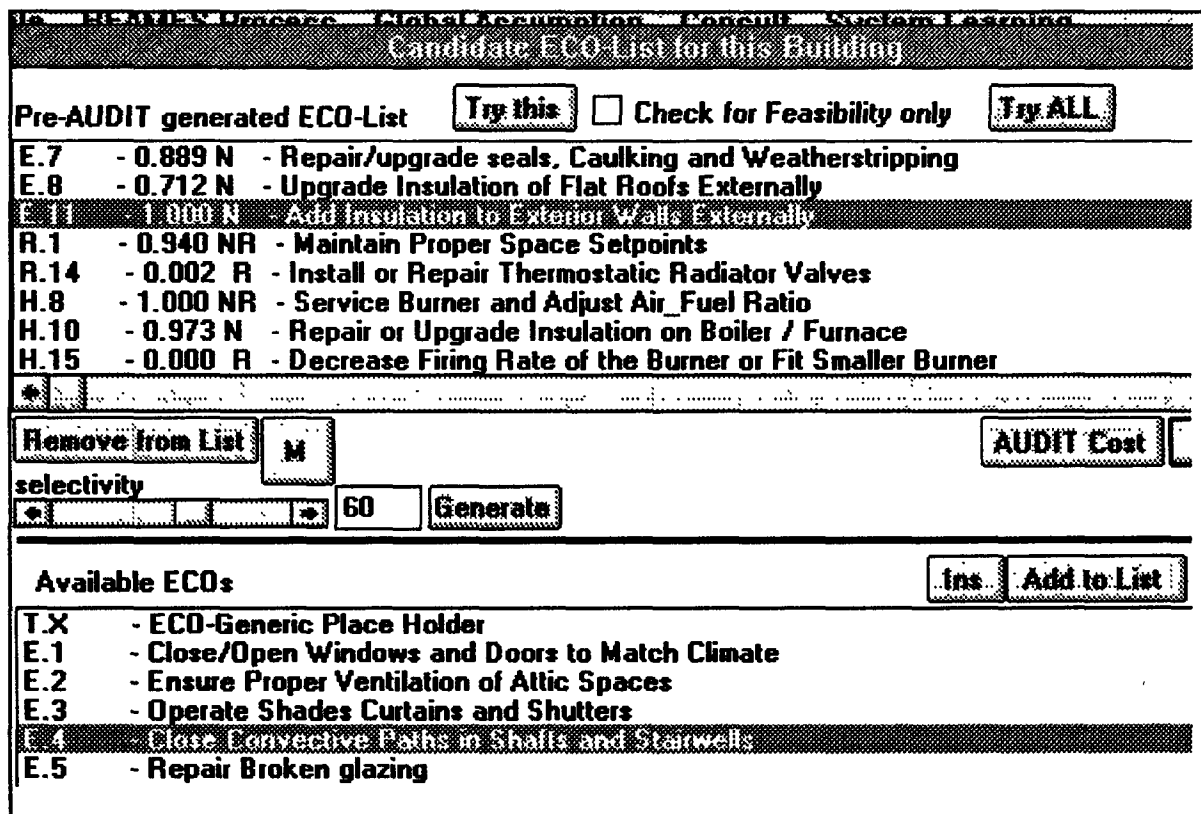


Figure 3.

preliminary conclusions and indications for the next audit phases. The pre-audit phase not only allows the auditor to know the necessary level of complexity (and cost) of the audit but also supplies a list of candidate ECOs on which the auditor can focus his attention and plan appropriate measurements. (Figure 3).

Using the preliminary information gathered with the "basic input", the model develops significant buildings indicators (Specific consumption ratios, A/V shape factor, etc.), which allow the building to be classified and makes a forecast of the likely energy conservation measures. This result is obtained by means of a Neural Network Pattern Associator (NNPA) that considers the characteristics of the specific building and compares this information with those embedded in a statistical module. This module contains the essential technical data and parameters of a sample building stock (currently, more than 100 buildings) and these data provide the basic knowledge for the pattern associator.

The candidate ECOs are determined not only by means of the NNPA but also according to the information directly provided by the building owner or manager. Other ECOs can be added according to the auditor's personal experience.

4.2. The Neural Networking concept and its application in BEAMES

Neural Networks (NN), connectionist models or neuromorphic systems are names of artificial systems based on operational principles thought to be similar to those of the human brain. These models consist of many simple neuron-like processing elements, called "units", interacting with each other by means of weighted connections. Each unit has a "state" or "activity level" determined by the inputs received by other units in the network. The weights modulate the relative importance of the incoming signal to each unit, thus encoding the relations of the state level of certain units with respect to others.

A neural network can be considered, in general, as a set of linked units able to connect an input phenomena, which can be described in a space of dimension n to an output result or command in a space of

dimension m . I/O relationships can be not only linear but of any kind.

Given a particular structure (topology) of the NN, this propagates the activation state from a first layer of units (called input units) to a number of intermediate layer units (called hidden units) which, in turn, propagate it to a final layer of units (called output units), all without backward connections. A general algorithm, called back-propagation, has been found (McClelland and Rumelhart, 1986 and 1988) to "train" the network by means of a sufficiently large set of "training cases". This algorithm performs a step by step correction of the weights using the feedback information of the error between the reconstructed state and the given state of the training set. This network topology has been proven to be effective in representing many classes of different problems, although its learning algorithm lacks "biological plausibility" (Figure 4).

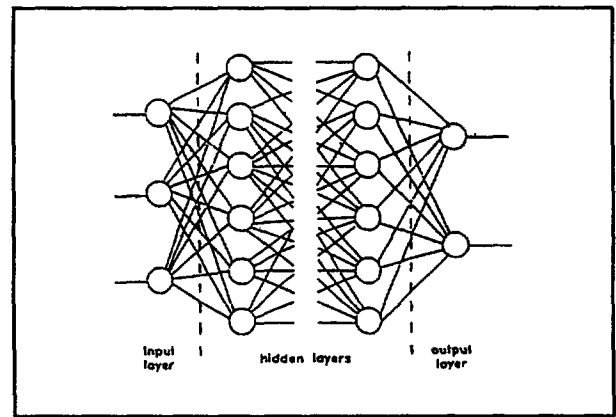


Figure 4.

Depending on the architecture of the network and on the assumptions concerning its operation, convergent algorithms may exist. On the basis of the knowledge of the state of a reduced number (subset) of units, these algorithms can compute a stable configuration of weights by means of which the available set of states and the complete network can be reconstructed with the best possible approximation. These "learning" algorithms make it possible to identify the Neural Network in an approximate way, the accuracy being improved as the number of training cases increases together with the knowledge of the network.

A Neural Network, whose weights have been adjusted to "learn" how to represent the remaining information of a finite collection of objects is able, given a piece of it, smoothly to interpolate the missing part from the partial information available on objects not belonging to the training set but supposed to have some relation with it. In this respect, NN can be thought of as generalised models adapted to a specific problem by means of best fitting techniques, and able to "discover" information structures hidden in available data sets.

Today, the simulated connectionist approach is available even on MS-DOS and WINDOWS-PC environment. Within BEAMES the NN has been used for solving the problem of deriving a detailed set of data from the rather incomplete input information available at pre-audit stage as network input (e.g. heated volume, construction/renovation year, boiler type and age, number of dwelling units, etc.). These partial building characteristics are fed into the NN in order to obtain as output, not only likely ECOs (e.g. insulation of exterior walls, regulation of the boiler firing rate, etc.), but also the disaggregation of energy consumption into various end-uses, building component dimensions, etc. The problem is encoded as a typical 3 layer feed forward NN (input layer, hidden layer, output layer), trained with the back-propagation algorithm. Data from real buildings on which ECOs have been implemented are used. In fact, the Neural Network Pattern Associator (NNPA) used in BEAMES elaborates its output results (suggestions) on the basis of a statistical knowledge of previous detailed building audits carried out in the past on real buildings.

No one today would agree to start medical treatment based only on the suggestions of a computer output. Similarly, a "Supervising Authority" (for instance an experienced auditor) must, each time, confirm that the information resulting from the operation of the NNPA is reasonable and meaningful for the building under consideration. As long as the auditing activity goes on, it is possible to update the statistical base available to the NN by adding all the audits that have been carried out with its help and judged reliable. Therefore, BEAMES itself acts, not only as a training tool for auditors but also has a self-learning process which allows it to include in its knowledge base all the technical improvements identified to date. With the learning procedure, it is also possible to insert into the network knowledge base the most recent and advanced ECOs and the energy performance of various types of buildings in different climatic conditions.

4.3. Additional Operational Features

The output recommendations are not limited to a list of ECOs but suggestions for maintenance work are also provided on the basis of the answers given to a simple non-technical input questionnaire on the condition of different building envelope components and equipment. A standard recommendation, which is

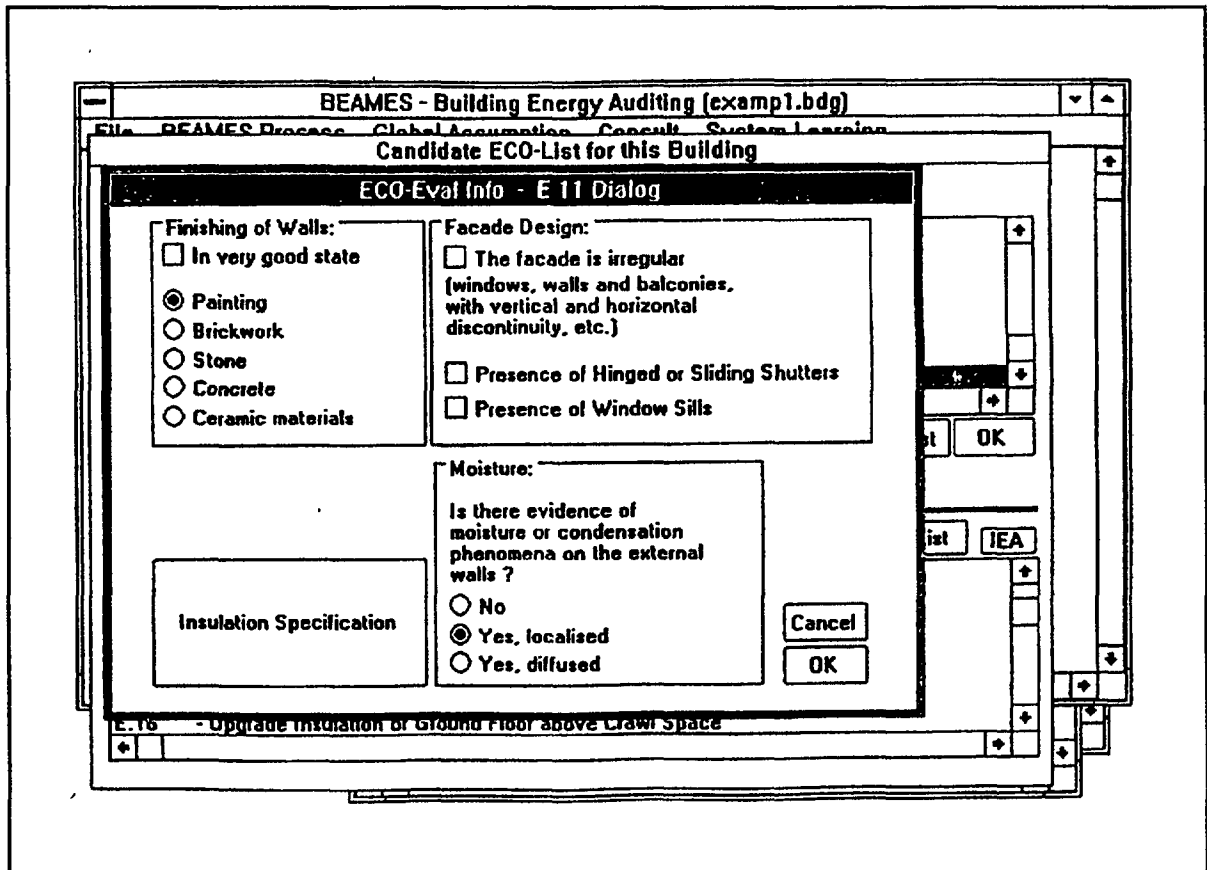


Figure 5.

printed automatically in the final report, corresponds to each answer .

This information is also taken into account when ECO implementation strategies have to be identified and suggested to the user.

For each candidate ECO of the pre-audit list, the auditor can decide on a detailed audit. BEAMES then displays new dedicated windows with specific questions concerning, first of all the feasibility of that ECO and, subsequently, technical data (Figure 5) .

BEAMES provides guided assistance for the audit procedures, the measurement techniques and the evaluation of each selected ECO. According to the ECO list, it also shows an indication of the approximate cost of carrying out the audit, which can be compared with the likely savings, making a cost-benefit analysis of the audit possible .

By means of suitable HELP commands, it is possible for the auditor to be guided and to navigate through all the information loaded in various parts of the package at any moment.

Technical and economic evaluation is performed according to price data specified for any ECO (Figure 6) and according to general financial assumptions set in the Menu Global Assumption (Figure 7). Since both technical and economic input data are affected by errors or uncertainties, the model performs an error

Insulation Specification

Existing surface on which to add extra insulation:

Area [m²] 1000 ± 30

Thermal transmittance (U-value) [W/m² C] 1.7 ± 0.2

Estimated normal maintenance costs per area unit without extra insulation [AU/m²] 20000 ± 5

Estimated normal maintenance fixed costs without extra insulation [AU] 1.5e+006 ± 200000

Estimated residual duration of existing building element [yr] 3 ± 1

Years for NET PRESENT VALUE and RATE OF RETURN Calculation 10 ± 0.5

Definitions & Formulas

OK Cancel

Extra insulation to be added:

Thermal conductivity of the insulation material [W/mC] 0.034 ± 0.005

Layer thickness [m] 0.06 ± 0.001

Insulation Cost [AU/m²] 70000 ± 7000

Additional Costs [AU/m²] 30000 ± 3000

Estimated fixed costs [AU] 1.5e+006 ± 200000

Estimated Duration [years] 20 ± 1

Overall Seasonal Efficiency: statistical default for this case 0.7 ± 0.03
0.83

Internal Temperature Setpoint [C] 22 ± 1

Thermal Mass: Low Medium High

Figure 6.

analysis (Bevington P.R. 1969, Taylor J.R.1982) on the computational results of the ECO under consideration.

Two user selectable alternative methods are used to perform this error analysis:

- A standard analytical Error Propagation, calculated using the first order partial derivative error components of the formulae used to evaluate the ECO.
- A Monte Carlo simulation technique, which estimates the dispersion of the results, recalculating several times all dependent values with different sets of input values at each step. These sets are generated taking input values with random perturbations within their specified error terms.

The Error Analysis is performed on all computations involved in ECO Analysis and chiefly on economic computations.

Dedicated reporting can be added to standard reporting, automatically prepared, once the energy conservation measures have been identified. This allows a considerable reduction in report drafting time and hence a cost reduction of the audit. The ECO evaluation report quotes the energy effects and several economic indicators for the cost-effectiveness of the investment.

Since evaluation procedures may vary from country to country, BEAMES can accept different calculation modules which have to be added and linked. In this way, BEAMES ensures flexibility in coping with local standards, norms and evaluation models.

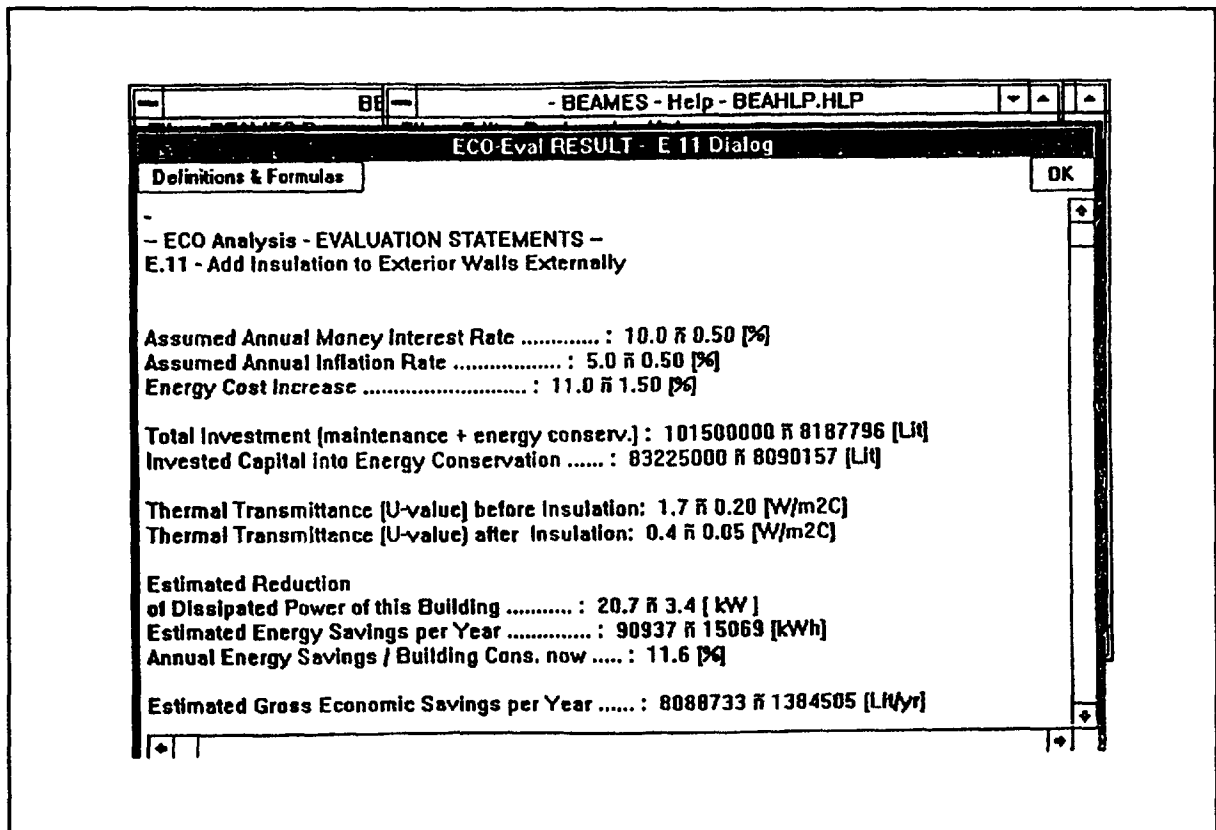


Figure 7.

5. CONCLUSIONS

The project described in this paper was started in order to foster the dissemination of advanced design tools with European norms and standards. The availability and use of such informatic tools should contribute to the modernisation of building design and construction techniques, which in the future are likely to be increasingly oriented, at least in Europe, to building renovation and retrofit.

The Building Energy Audit Management Expert System (BEAMES), demonstrates the potential of tools based on Artificial Intelligence, to make impressive improvements in existing auditing techniques. The present prototype is, in fact, a skeletal version of the final product, which can be developed from it by "fleshing out" the various elements of the system. This will require a great deal of information and knowledge, however, and the JRC does not intend to develop the tool further on its own. It regards the prototype as a basis on which the full version can best be built with the help of an international co-operative network which it intends to set up.

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