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A PROTOTYPE EXPERT SYSTEM FOR LARGE SCALE ENERGY AUDITING IN BUILDINGS

B. CAUDANA,† F. CONTI,† G. HELCKE‡ and R. PAGANI†
† SOFTECH Energia Tecnologia e Ambiente, Via Cerrnaia 1, 10121 Torino, Italy
‡ Commission of European Communities, Joint Research Centre, Ispra Establishment- TP 261, 21020 Ispra (Varese), Italy

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Abstract—A brief discussion is presented of the increasingly important role being played by informatic techniques in the building sector. Computer aided design packages for the architect have existed for some time, but other types of software are also needed now. The profusion and complexity of norms and standards, together with the large number of technical solutions available, make it very difficult to master all the knowledge required for building design and retrofit without informatic help. This is particularly true in building energy auditing, which is an essential prelude to the retrofitting of older buildings. To illustrate the way ahead, an expert system being developed by the Joint Research Centre is described. This system, known as BEAMES, employs a neural network allowing the system to "learn" from the experience of past audits.

Energy audit   Energy savings in buildings   Artificial intelligence   Neural network

1. PERSPECTIVE OF ADAPTIVE INTELLIGENT TOOLS IN THE BUILDING SECTOR

The building sector requires increasing attention from policy makers and industrialists because of its growing impact on people's lives.

- Much of Europe's population lives in big old towns and urban problems are coming to the fore;
- due to the very long lifetime of buildings, poorly performing constructions produce negative impacts for many decades, making the solving of the associated energy and environmental problems more difficult;
- the building sector is that in which the highest energy consumption and wastes occur and it will become the principal target of energy conservation (demand side management) actions;
- problems of mobility and pollution are strictly related to urban layout, which is rapidly becoming inadequate for new living conditions and technologies;
- the building industry is a particularly conservative one and the introduction of informatic tools, at the design, maintenance and operational level, can become an opportunity for its modernization.

For all these reasons, it is very likely that towns of the next century will not be very different in their external apperance from today's towns. This is particularly true for Europe, where the land available for new construction is limited and a vast patrimony of historical buildings has to be conserved.

We are living in a period which has been characterized by the so-called informatic revolution. The application of automatic computing techniques is spread, worldwide, over nearly all aspects of human activity, energy use in buildings included. Most of the scientific and technical improvements occur today in the fields of heating and air conditioning systems, control and regulation, home and office appliances, communications, maintenance and service management where replacement is more rapid. In the future this trend will be even more marked.

Hard- and software products have already been developed for several applications in the building sector and a terminology has been created to describe these new applications. The French word "domotique", and the English "smart houses", "intelligent" windows etc. are all examples of these new terms for informatic applications to buildings or building components.

The development of an energy and informatics industry in the building sector has been under way for many years. Several control and regulation systems for HVAC plant have attained levels of sophistication that would have been impossible without the adoption of informatic tools. Today, the services of most, up-to-date, large buildings are controlled by building-energy management systems (BEMS) which have several operational functions. These concern not only the management of heating and cooling systems for a healthy and thermally comfortable working space, but also the optimum control of appliances and building automation and, more generally, the planning of most important activities such as maintenance, internal mobility, security, and so on.

Moreover, these BEMS are increasingly becoming an essential component of the new building design techniques based on bioclimatic or solar passive concepts. Here again, the degree of complexity of the building system, which foresees different flow paths of the air, according to external climatic conditions and to occupants' requirements, makes it necessary to install intelligent devices which can ensure the building system operation in an automatic way.

Over the past few years, efforts to encourage faster and deeper penetration of advanced informatic technologies in the buildings sector have increased. Many scientific organizations, industrial associations and energy utilities are sponsoring meetings and conferences on future buildings in order to identify both the most likely trends of technological development in the building sector and informatic applications for improving home and office services. The Future Building Forum activity, carried out in the framework of the International Energy Agency (Implementing Agreement on Energy Conservation in Buildings) is considering research tasks in many new scientific fields, where the use of advanced informatic "intelligent" tools is essential. Table 1 shows a list of these advanced topics applied to buildings.

The introduction of new energy supply systems such as decentralized cogeneration of heat and power (CHP), photo-voltaic systems and fuel cell generators, will be possible, provided that the technological, economic, environmental and acceptance problems are overcome. On the energy demand side, the extensive implementation of new energy efficiency measures can provide rapid and cost-effective improvements to urgent environmental problems.

In fact, greater concern for environmental and safety risks is producing many more stringent norms. This fact, together with the need to take into account a large number of technical effects, will make the extensive use of intelligent means for mastering every activity, from the design stage up to the operation and disposal or recycling stage, increasingly necessary.

The use of adaptive intelligent devices will be aimed, not only at improving individual welfare, in terms of increased comfort and security levels, better indoor air quality, reduced expenditure on energy bills, etc., but also at coping with social goals or constraints, such as reduction of energy consumption and fuel emissions in order to minimize global warming or local pollution, optimum management of garbage and water disposal, etc.

2. REASONS FOR THE DEVELOPMENT OF NEW DESIGN AND RETROFIT TOOLS

If the trend described above continues, it implies that an equal weight be given both to the means for updating existing and obsolete building stock and to the development of innovative concepts for new buildings. Of the many new techniques for energy conservation and environmental protection, a very high proportion is applicable to both new and existing buildings.

The energy saving potential of advanced construction techniques and building energy automation systems is high: 30–40% with the best available technology and up to 75% with the best prototype technology.

Implementation of the best currently available techniques in a new construction will not, however, eliminate the need for a building retrofit in 20 or 30 years time. This is due in particular to the rapid obsolescence of informatic products and of some building and plant components. On the other hand, speeding up the commercialization of prototype technologies could bring early improvements in energy consumption levels. The setting up of advanced new techniques of building retrofit is, therefore, something that will become increasingly urgent as time passes.

In fact, growing pressure for such advanced techniques is due to:

Table 1. Advanced technical systems and technologies for future buildings

System engineering:
- building product data base;
- building energy automation system structures and models;
- multi-function components;
- interface specifications;
- sensor and detector technologies;
- advanced electrical installation systems.

Operational technologies:
- advanced control concepts (fuzzy logic, neural networks, optimal predictive control, identification techniques, etc.);
- man-machine interface-functional requirements;
- fault detection with automatic recovery;
- multitask building energy management systems;
- remote control and monitoring technologies.

Advanced concepts:
- new energy conversion and concepts, such as fuel cell, PV, bioenergy, etc.;
- new building envelope "intelligent" components and sub-assemblies;
- new space conditioning strategies and systems;
- integration of new energy saving components with new energy conversion concepts;
- users' needs, expectations and acceptance of new technologies.

(1) the need for a reconversion of the building industry from the field of new construction to that of retrofit, and

(2) the increasing social awareness of energy and environmental problems which will lead to extensive specific retrofit actions.

These requirements have led scientific organizations to pay particular attention to the development of sophisticated design tools both for new buildings and for retrofit actions on existing buildings. The goal of these new tools is to serve as a guide both for design and educational tasks.

Today's trend is, on the one side, to develop and translate the most practical aspect of building science and related norms into software, for use on Personal Computers or Microcomputer stations by the architectural and engineering professions and on the other to develop new modelling techniques (particularly in areas such as lighting and daylighting, which have received less attention in the past) and to integrate or interface them with other models or information systems. For instance, the interfacing of thermal calculation models with CAD packages and with energy and architectural databases can provide very effective and powerful assistance to building architects and energy designers.

The use of hypermedia makes it possible to link data and images in a nonlinear manner, allowing users to navigate through different texts, to search at the right moment and quickly for the information required and to customize their approach, based on their current needs. The use of hypermedia-based technology also supports extensive use of animation and video to ex-

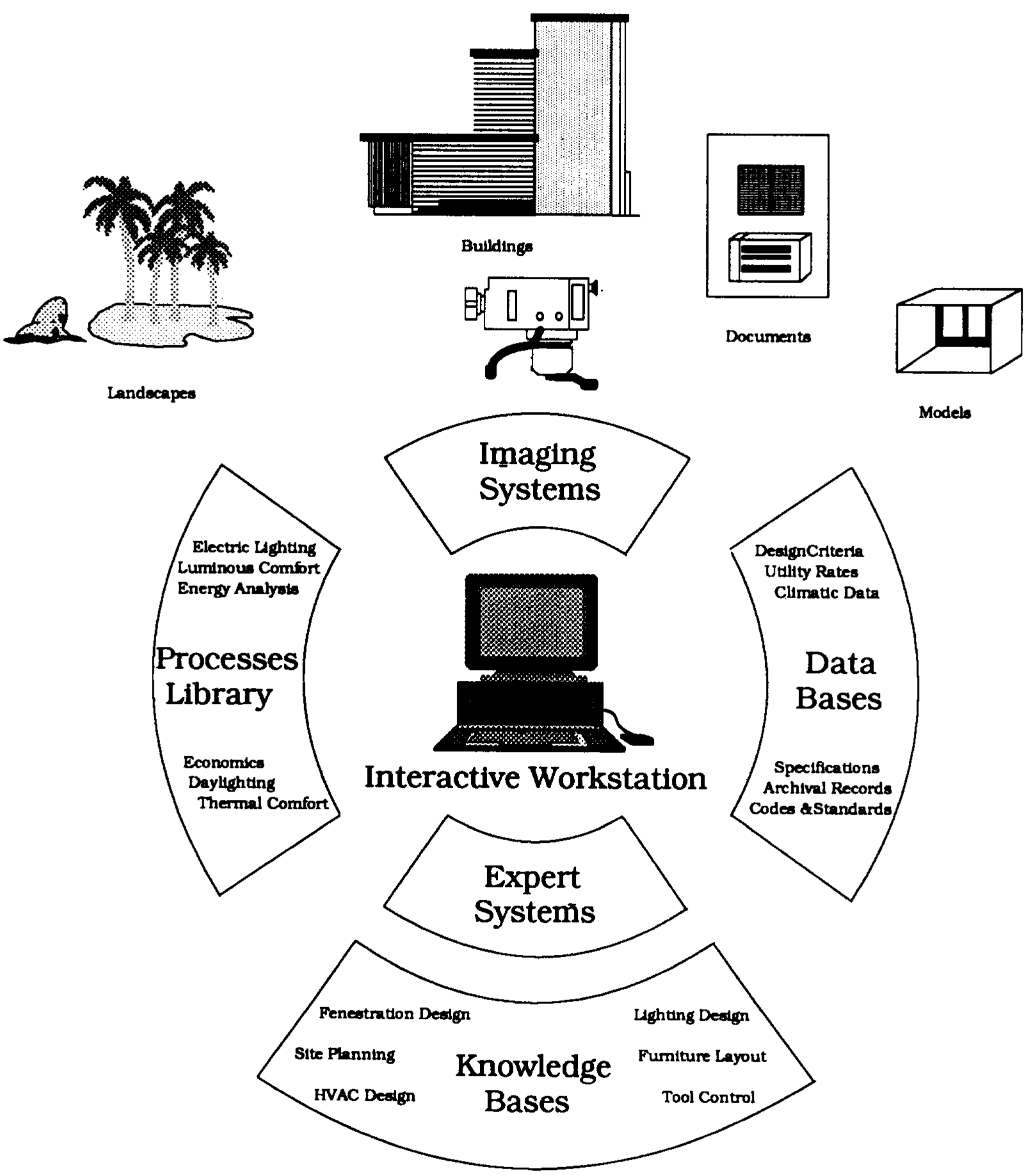

Fig. 1. Lawrence Berkely Laboratory envelope design tool.

plain concepts and this is particularly important for educational and training purposes.

Examples of such developments are presented in Fig. 1 where a network of interacting programs developed at Lawrence Berkeley Laboratory is shown. Preliminary work of component development aimed at a similar goal has been carried out at the JRC/ISEI, Ispra, during R&D work for regional energy saving planning actions (Fig. 2). A very ambitious project (COMBINE) is under development in Europe, aimed at creating a communication environment for energy and buildings design modules.

The way in which informatic techniques are being used to improve the energy performance of building stocks, is well illustrated by the example of a prototype expert system for building energy auditing, being developed by the authors. This system (called BEAMES) utilizes the neural network concept which has recently emerged from studies of the functioning of the human brain.

The need for an expert system in this area was highlighted by a study[1] in which a benchmark comparison of commercial energy auditing methods showed that little agreement exists between the recommendations and no correlation between the cost and the accuracy of various commercial audits. The need for standard methodologies in the field of building auditing and for the use of common European norms and standards was evident.

Moreover, the JRC participated in the activity of the IEA task XI energy auditing, whose final product was a two volume "Source Book" published in 1987.[2] In it, between 200 and 300 energy conservation options (ECOs), often interacting each other, were described together with different implementation strategies according to specific situations. This work was continued at the JRC, where other ECOs, derived from the most recent applications of bioclimatic architecture, were added to the long list of annotated ECOs. It became

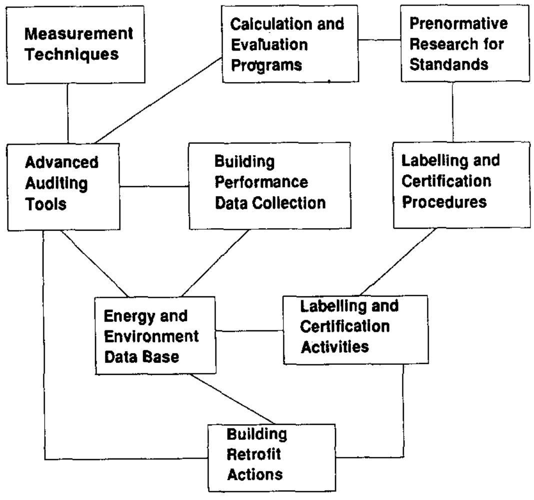

Fig. 2. Integrated operative tools for carrying out energy savings in a regional building stock.

clear that the links and interconnections between ECOs, analysis and measurement techniques, and audit procedures, could only be mastered by loading and managing the knowledge on a computer.

It was therefore decided, during 1990, to develop an energy management expert system with the aim of improving the energy auditing of existing buildings. This informatic tool, of which a demonstration prototype (for residential buildings) has now been developed, can give an impressive idea of how advanced mathematical algorithms and recent advances in artificial intelligence can find practical application and greatly enhance auditing techniques. The product is mainly addressed to:

(1) the large number of professionals (engineers, architects, technicians) who will be responsible for building energy certification, which is an increasingly important requirement for building and/or urban area retrofit actions;

(2) 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 will be available within a few years, by which time this tool can 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, all have to be borne in mind and optimum decisions made quickly and efficiently. It is almost impossible for professionals, no matter how expert they may be, to master all this knowledge efficiently without advanced informatic tools.

(2) To ensure the reliability and completeness of the audits. As the JRC benchmark experiment demonstrates,[1] commercial audits provide different recommendations depending on:

- the scheme used;
- the auditor's training;
- ECO implementation strategies,
- national norms, etc.

(3) To improve the audit cost-effectiveness. Tariffs for audits are fixed in these European countries in which building energy audits are required for Building Energy Certification or Labelling procedures, as required by European Directive proposals.[3] The audit quality could be greatly enhanced, however, 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 are 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.

(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.

3. DESCRIPTION OF THE MAIN PERFORMANCE FEATURES OF BEAMES

BEAMES is a demonstration program oriented to 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 most suitable 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 thermal and physical and geometrical data in order to be able to identify, by means of mathematical 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 required during the site visit. As a result, the auditor cannot properly plan the visit beforehand or evaluate its cost and be sure of the completeness of the audit.

The BEAMES program utilizes the "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 (Fig. 3). In the early audit phase only a small amount of information, which can be provided also by non-technical people (such as the building owner or administrator) is gathered (Fig. 4). BEAMES then develops 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 (Fig. 5).

This result is obtained by means of a neural network pattern associator that considers the characteristics of the specific building and compares this information with that embedded in a statistical module. This module contains the essential technical data and parameters of a sample building stock (currently, more than 100

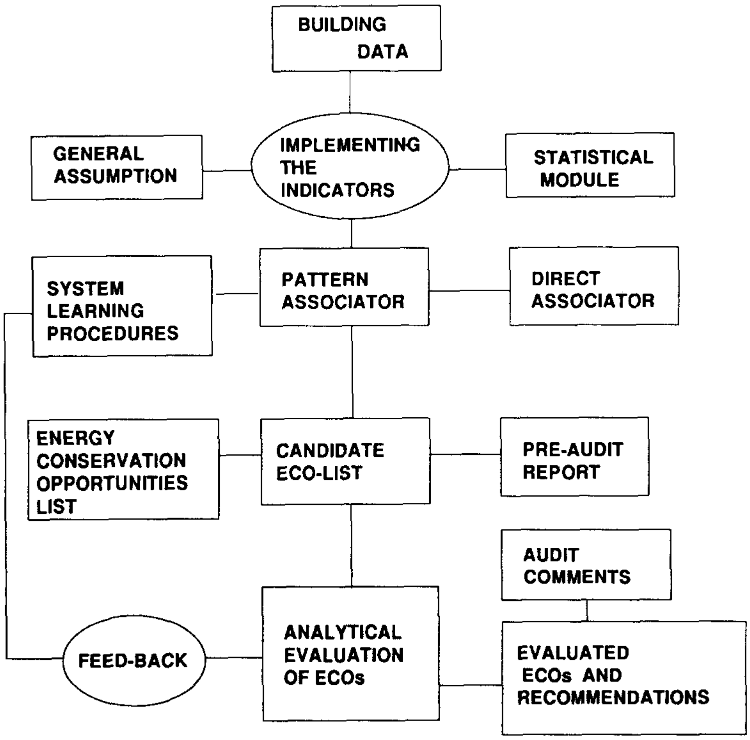

Fig. 3. BEAMES model logic structure.

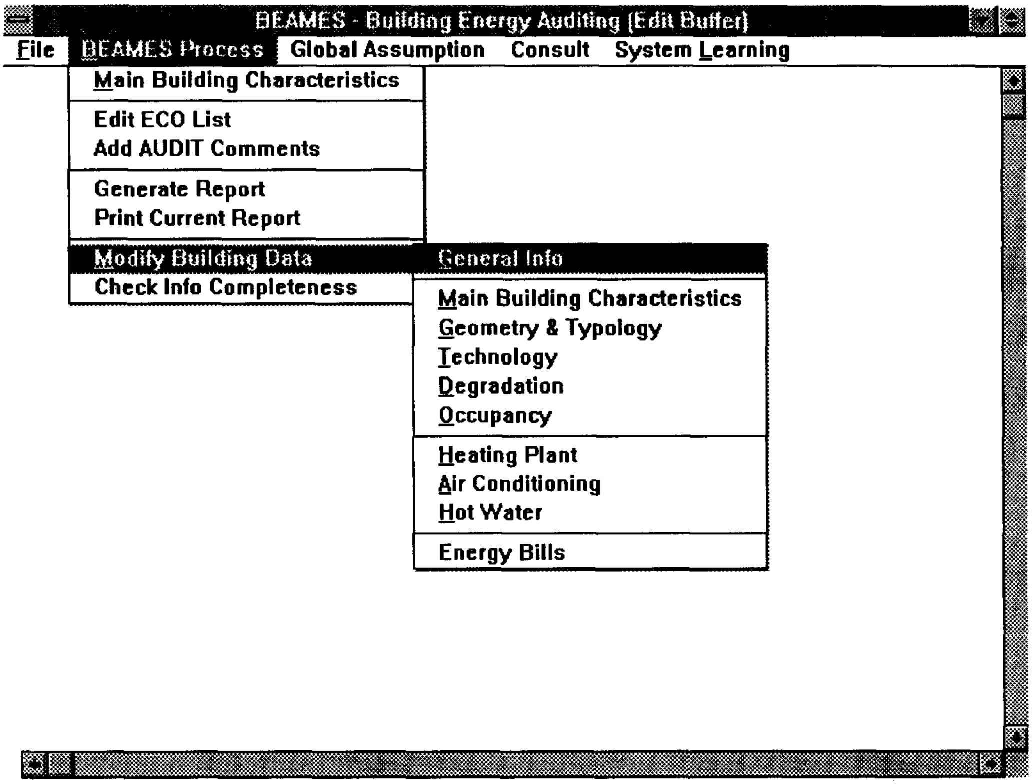

Fig. 4. Input data pull-down menu.

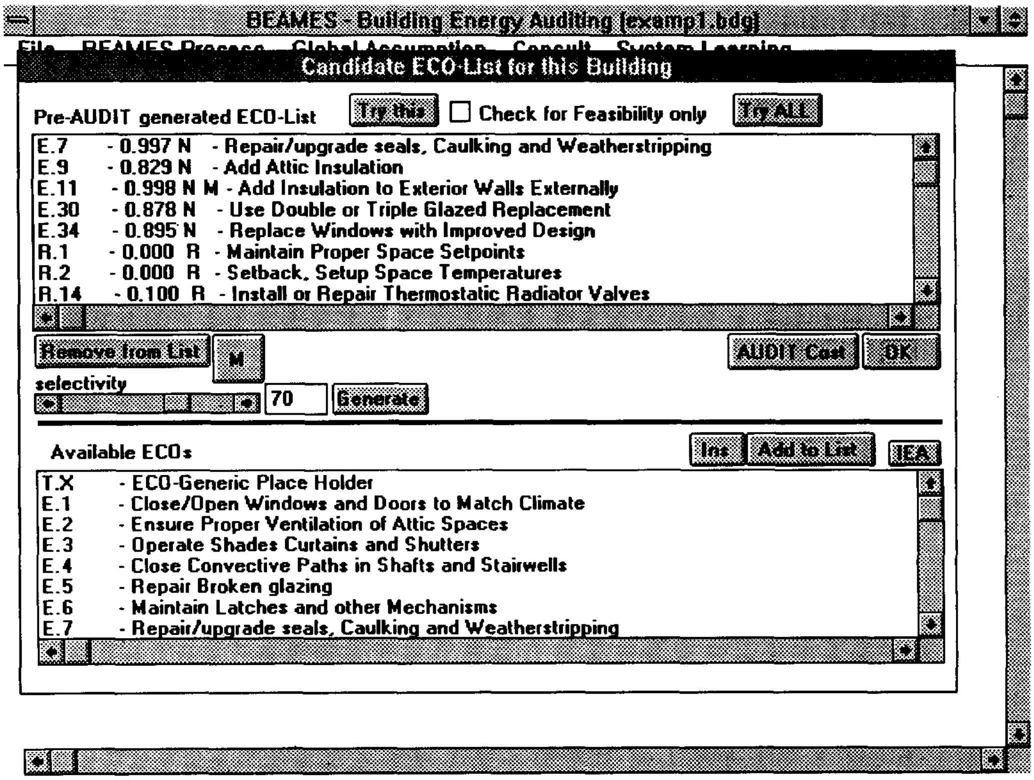

Fig. 5. Example of BEAMES pre-audit phase output with the list of the likely energy conservation opportunities for the building under investigation in the upper part of the screen.

buildings) and these data provide the basic knowledge for the pattern associator.

Once the likely ECOs for the specific building are identified in the pre-audit phase, BEAMES provides guided assistance for

(a) measurement techniques;
(b) audit procedures; and
(c) evaluation or analysis technique taking into account implementation strategy options.

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 in the audit.

4. THE NEURAL NETWORKING CONCEPT AND ITS APPLICATION IN BEAMES

Neural network (NN), connectionist models or neuromorphic systems are names of artificial systems based on operational principles 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 input 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 phenomenon, 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. The network has an initial learning mode, in which an input is given to the network together with the corresponding output, and weights are determined so that the network is "trained" to produce the desired output when it sees something like the training input.

A general algorithm, called back-propagation, has been found to "train" the network by means of a sufficiently large set of "training cases".[4,5] 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 proved to be effective in representing many classes of different problems, although its learning algorithm lacks "biological plausibility" (Fig. 6).

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

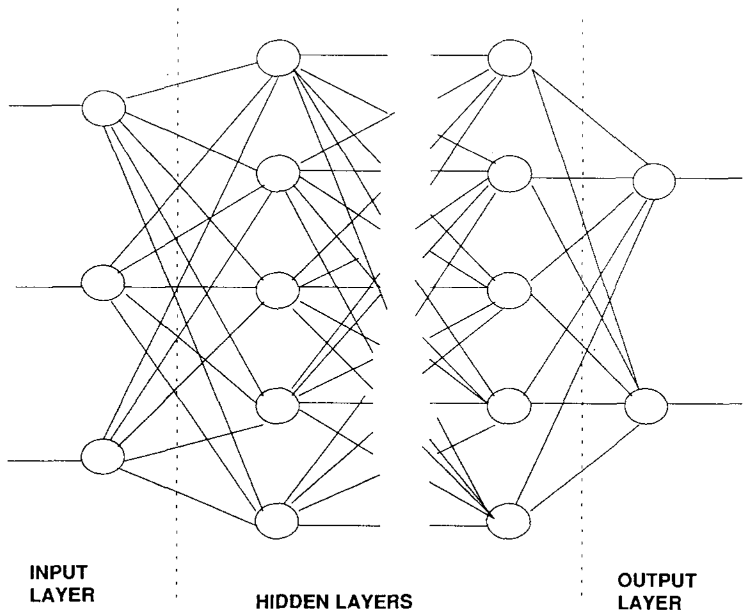

Fig. 6. Schematic diagram of typical neural connections in a part of a neural net. Circles represent neurons connected each other by weights.

accuracy being improved as the number of training cases increases and, with it, 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, to interpolate the missing part smoothly from the partial information available on objects not belonging to the training set but supposed to have some relation with it. In this respect, NNs can be thought of as generalized models adapted to a specific problem by means of "best fit" 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 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. This 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 have been 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.

Today, no one would agree to start a medical treatment based only on 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 far as the auditing activity goes, it is possible to update the statistical base used by the NN by adding all the audits that have been carried out and judged reliable.

Thus, BEAMES acts not only as a training tool for auditors but also as a self-learning procedure which allows it to include in its knowledge all the technical improvements which have occurred so far.

5. CONCLUSION

The availability and use of advanced informatic tools will contribute to the modernization of building design and construction techniques, which in the future will be more and more oriented, at least in Europe, to building renovation and retrofit. Hypertexts using knowledge stored in various media (CD, video, etc.) will make it possible to master the huge amount of knowledge needed for coping with multicriteria decisions and constrains.

The building energy audit management system developed by the JRC to a prototype stage is an example of how advanced informatic techniques, based on artificial intelligence, can make impressive improvements in existing auditing techniques. The JRC does not intend to develop this tool alone. It started the project in order to foster the dissemination of advanced design tools with European norms and standards. The JRC considers it as a proposal for setting up an international cooperative network aimed at the full development of the expert system presented.

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About the Author—FLAVIO CONTI is a graduate in electrical engineering at the University of Genoa in 1962, in Nuclear Engineering at University of Bologna in 1967, in Social and Economic Science at University of Milan in 1990. EC scientific officer since 1962, he has gained a wide experience in many energy sectors, from nuclear energy to energy scenarios and strategies, to renewable energies and energy efficiency. Particularly expert in the problems of energy conservation, in general, and building energy auditing techniques. He is presently charged of the JRC of the support action to the Commission of EC to the THERMIE and SAVE programmes for energy efficiency in buildings. Member of the IEA Executive Committee for Energy Conservation in Buildings on behalf of the CEC.

About the Author—GEORGE HELCKÉ is a British physicist, awarded Ph.D. for study of structure of myoglobin single crystals using electron spin resonance (ESR). He was recruited by Joint Research Centre

of European Commission to make ESR study of radiation damage in biological materials. He spent several fruitful years in this activity before moving to energy field in 1976. He published *The Energy Saving Guide* to assessing energy saving investments in 1981 (Pergamon Press). Conceived and carried out award winning comparison of commercial energy auditing of buildings by inviting for separate companies from three countries to audit same set of occupied, benchmark buildings (1987). Participated in IEA annex on energy auditing of buildings. Consultant to Directorate General XVII (Energy) of European Commission.

About the Author—ROBERTO PAGANI got a University Degree in Architectural Technology at the Turin Polytechnic in 1977 and developed his research experience in the U.S.A. (1979–1980). Invited Professor of "Analysis of Energy Systems" at the Polytechnic of Turin, Pagani is author or co-author of 13 books and more than 40 scientific and technical publications. Since 1990 he is an independent expert of the Commission of the European Communities, Directorate General for Energy DG XVII. R. Pagani is the director of SOFTECH S.r.l. consultancy and research group in the field of energy and environmental planning. He provides to regional and town governments appropriate schemes to manage investments and incentives in energy conservation and fuel substitution, in conjunction with building maintenance programmes.

About the Author—BRUNO CAUDANA is researcher at SOFTECH S.r.l. and at Adaptive Systems S.a.s. in Turin. He has acquired several years experience in algorithm design, software development of real time devices and control measurement systems for aerospace test equipment and process control. He is currently involved in research projects and professional activities focused on the application of the neural network computation approach. His theoretical interest now focus on artificial life aspects related to subsymbolic and biologically plausible computation paradigms.