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Autor: Calvi, Gian Michele / Peano, Alberto / Salvaneschi, Paolo

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Expert System for the Diagnosis and Rehabilitation of Building Structures

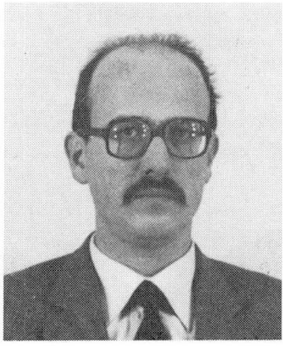
Système expert pour l'évaluation et la réhabilitation des bâtiments

Expertensystem zur Diagnose und Therapie von Bauwerken

Gian Michele CALVI
Dr. Eng.
Univ. of Pavia
Pavia, Italy

Born 1957, received his Master of Science in Civil Engineering from the University of California, Berkeley, and his Ph.D. in Structural Engineering from the Politecnico di Milano. His main research interests are related to the seismic behaviour of structures, with emphasis on design and analysis of reinforced concrete and masonry structures, having been active both in the experimental and numerical fields. He is now research engineer at the Department of Structural Mechanics of the University of Pavia.

Alberto PEANO
Dr. Eng.
ISMES
Bergamo, Italy



Born 1946, received his Doctoral Degree at Washington University, St. Louis, Missouri. He has worked in the industry as a stress analyst as well as in the Politecnico di Milano as an assistant at the Department of Structural Engineering. Since 1980 he is Head of the Mathematical Modelling Division at ISMES. Today he is Research and Development Director of ISMES.

Paolo SALVANESCHI
Physicist
ISMES
Bergamo, Italy

Born 1948, received his Physics Degree at the University of Milano. For 12 years he has been working in industry, managing software development teams, designing software for process control and engineering/scientific applications and consulting in Software Engineering. Now he is responsible of the Artificial Intelligence unit and of the Software Engineering/CAD systems Development Unit of ISMES.

SUMMARY
A knowledge based system, whose objectives are to support the procedures which lead to the seismic risk evaluation of buildings and to suggest possible retrofitting, is presented. The system architecture and its principal functions are described, with emphasis on the main part of the system: a model («artificial world») which describes the structure and possible behaviour of the building and its environment, at different definition levels, with qualitative and/or quantitative attributes.

RESUME
Cet article présente un système de traitement des bases de connaissances permettant l'évaluation du risque sismique pour les bâtiments et suggérant des mesures. L'architecture du système et ses principales fonctions sont décrits, plus particulièrement, la partie principale du système: un modèle («artificial world») décrivent la structure et le comportement possible des bâtiments et de leur environnement à différents niveaux de définition, avec attributs qualitatifs et/ou quantitatifs.

ZUSAMMENFASSUNG
Der Artikel stellt ein wissensbasiertes System vor, das für die Ermittlung des Erbebenrisikos von Gebäuden verwendet wird. Vorschläge für bauliche Verstärkungen werden beschrieben. Der Aufbau des Systems und die Hauptfunktionen werden erläutert, wobei das Hauptgewicht auf jenes Modell gelegt wird, das einer «künstlichen Welt» gleich, das Gebäude, sein Verhalten und seine Umwelt auf verschiedenen definierten Ebenen qualitativ und/oder quantitativ beschreibt.

1. Foreword

In the last few years the importance of retrofitting existing buildings in order to obtain a uniform level of safety in case of seismic events has been widely recognized as a major problem.
The procedures required to establish a diagnosis and to suggest a therapy either for a single building or for classes of buildings, characterized on geographical bases or on the base of common attributes, are complex and heterogeneous, requiring either theoretical knowledge and practical experience. A building can be examined on the base of direct observations, in situ or laboratory tests and numerical analysis, and subsequently retrofitted; but a rational way of operating would require a step by step economical evaluation of the risk related to a vulnerable situation, of the improvements obtainable by different possible interventions, of a deeper knowledge obtainable by new tests and analyses.

2.Objectives

Objective of the research described in this paper is the design and implementation of a system which uses artificial intelligence techniques to face the complexity of the problem.
Some features of such system have to be:

- to support the evaluation of seismic risk and to suggest possible retrofitting interventions, either for single buildings and for classes of buildings;
- to support data acquisition (planning surveys, measurements and tests), and management (storaging of information, generalization of knowledge from a specific building to groups of buildings);
- to exert control over the use of a "movable laboratory" endowed with experimental and numerical facilities.

It is well understood that the treatment of uncertainties related to knowledge and procedures plays a fundamental rôle in such a system; nevertheless in what follows this topic will not be properly addressed, since it can be treated separately from the development of the main body of the system.
In a first phase of the project the whole system will be oriented only to masonry buildings, and afterward extended to reinforced concrete buildings, monuments, life-lines and so on.

3. Deep knowledge expert systems

Research and development in the expert systems field have initially produced shallow knowledge systems, i.e. systems based on empirical knowledge, judgement, heuristics. These components represent only a part of the knowledge needed to solve problems in many fields (civil engineering is among these), and limits and problems of first generation expert systems have been clearly stated (e.g. [1]).
Second generation expert systems are trying to combinate shallow and deep knowledge (causal and algorithmic knowledge) (e.g. [2,3]).
This objective is pursued by the system described in what follows, through the creation of a model of the real world ("artificial world" [4]) which has its own structure and can exhibit behaviours. Either structural and behavioural models are hierarchically built at several depth levels [5].

4. The system architecture

The system is built on three main layers (fig. 1):

- model or artificial world;
- functions;
- man-machine interface.

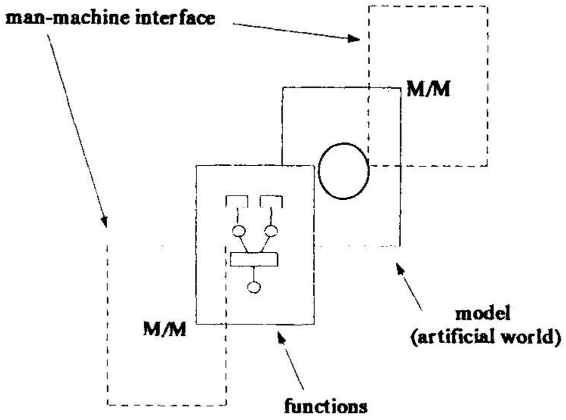


Fig. 1) System architecture

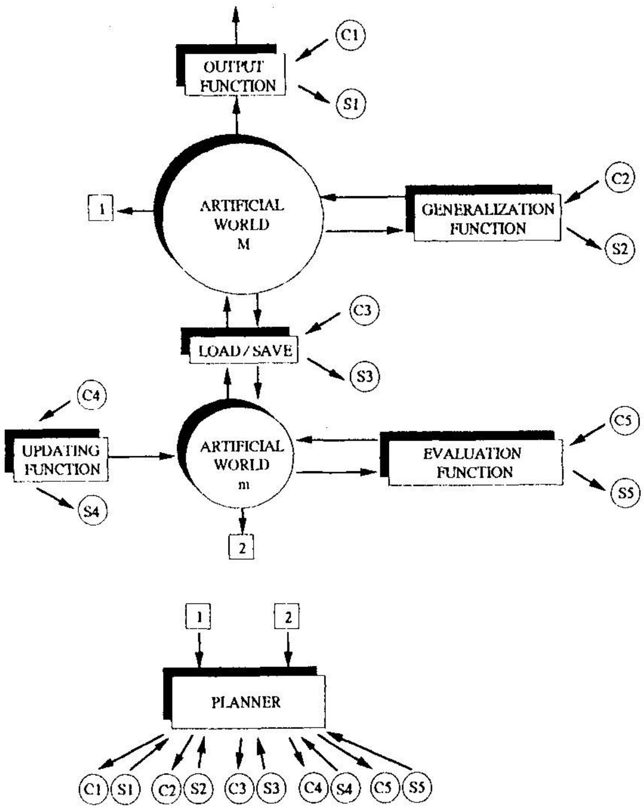


Fig. 2) Artificial world and functions

The artificial world depends on the case to be dealt with. For example it may be the model of a building, endowed with all the shallow and deep knowledge on structure and behaviour of the building itself, if the objective is the evaluation of the seismic risk of that single building, but it may represent the buildings of a village (or of a region) on the whole, as well.
In other words the constitution of the model can be seen as the implementation of a simulator through artificial intelligence software techniques.

The functions are possible operations related to the artificial world. Example of functions are:

- getting information from the real world to refine the model;
- simulating a seismic event on the model to evaluate the expected damage.

The man-machine interface allows the interaction between system and operator providing transparency to model and functions.

The structure of artificial world and functions are shown in figure 2:

- The artificial world "m" is a model of a single building and its environment.
- The "evaluation function" gets informations from "m" to produce a discussed risk evaluation together with a list of possible improving interventions and their estimated cost.
- The "updating function" modifies the attributes of the model "m" when more data are available either from observations, measurements, experimental tests.
- The artificial world "M" is a model of a class of building, modelled as a type building representing the class on the whole, subdivided into subclasses (different building types). Each single building is seen as a specific instance of one of the building types.
  Class, subclasses and instances are related through a inheritance mechanism; all the objects in the hierarchy have the same structure and the same potential attributes of "m" (fig. 3).
- "M" and "m" are related by a load/save function which can move objects from one to the other and viceversa.
- The output function allows outputs for the representation of "M".

Two last important performances of the system have to be mentioned:

- A generalization function can spread some attribute of specific buildings over whole classes or subclasses. This can be performed on statistical bases - when some information is available only for some building in a class, mean values can be generated and attributed to all other buildings - or on deterministic bases - if, e.g., an expensive experimental test has been performed on a building, some results may be attributed to other buildings recognized by a generalization algorithm -.
- A planner is making decision on data acquisition, evaluation, testing, numerical analysis, generalization of results, depending on budget, specific objectives and general seismic protections philosophy.
  In other words the planner acts as the control panel of the system, being able of suggesting a strategy, activating all the system functions and collecting information related to the plan of action (through commands C1÷C5 and status S1÷S5 in figure 2).

5. The building model

As already pointed out the building model collects all the knowledge related to a building and its environment organizing it in the form of attributes which can be originated by observations and tests. Structure and behaviour of the system are also modeled at different depth level with hierarchical relations.
As a result the model can be represented by a point in a 3D space (fig. 4). Moving from one point to another one means to have more information or to use a more refined structure or to simulate a more complex behaviour.
Generally any movement requires the investment of funds, either to acquire or to manipulate more information.

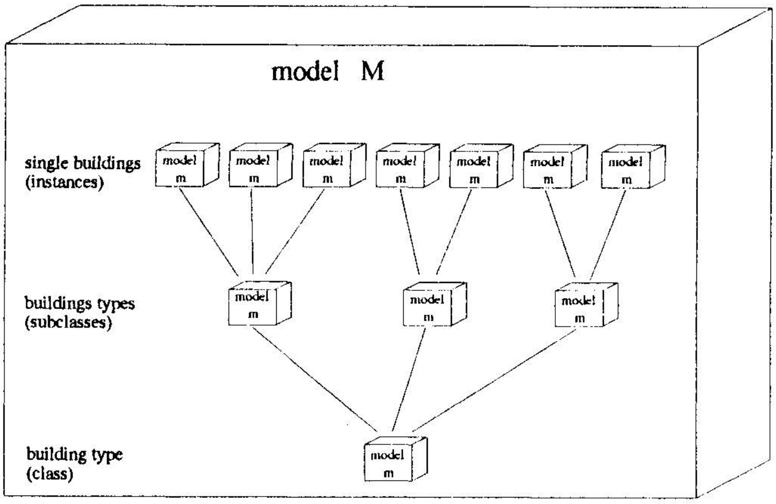


Fig. 3) The artificial world M

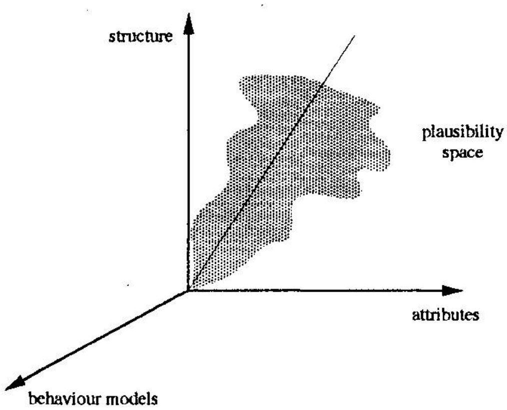


Fig. 4) The 3D space of the model

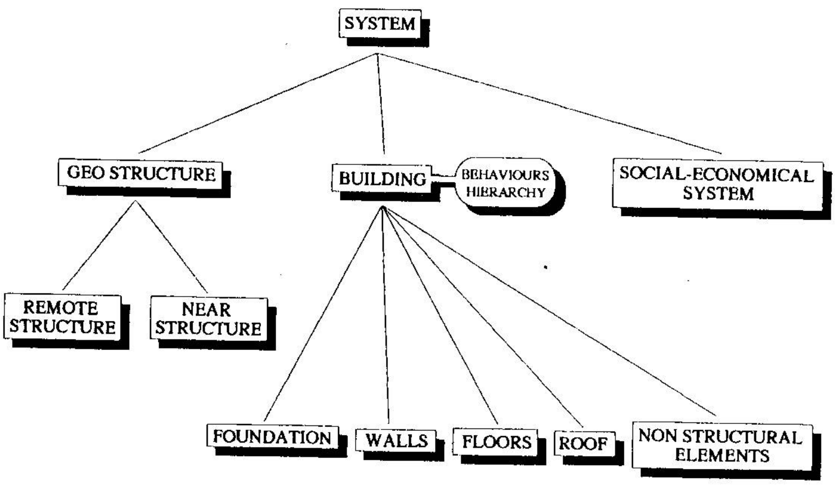


Fig. 5) The hierarchy of the structure

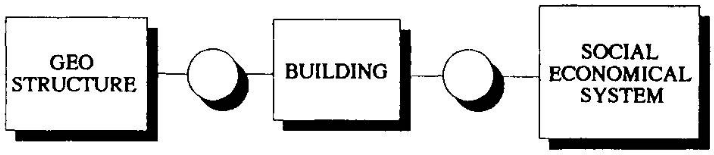


Fig. 6) First level of the structure

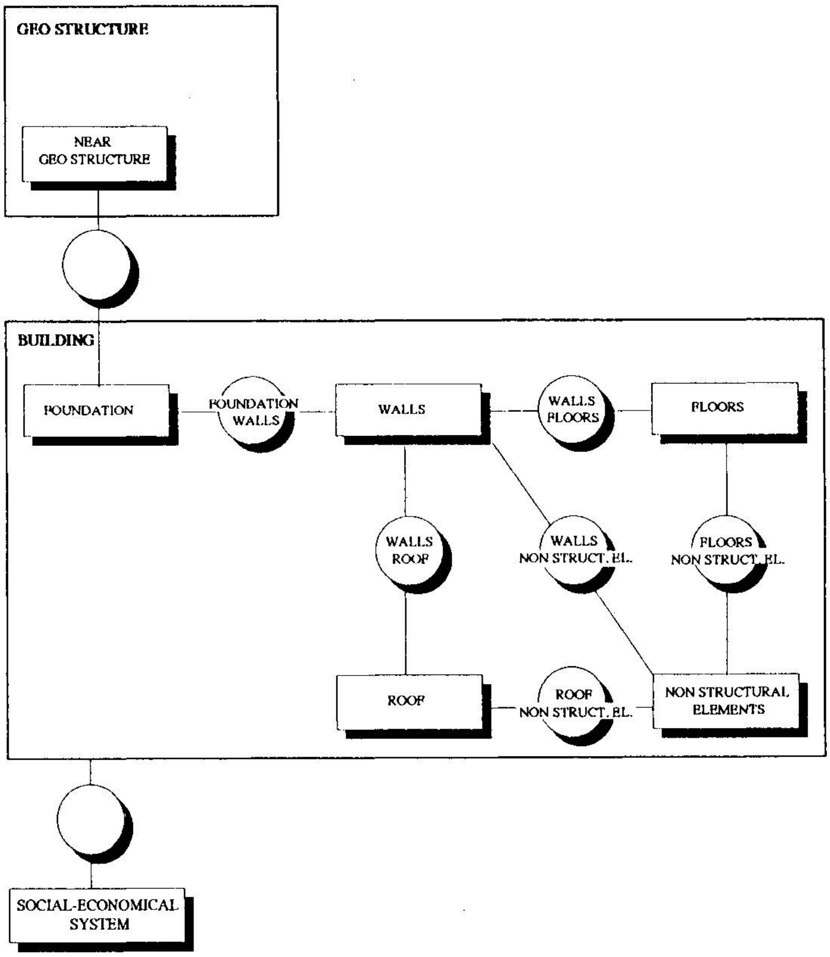


Fig. 7) Second level of the structure

Obviously it is not possible to reach any desired point in the space, but restrictions do exist (e.g. a numerical simulation might require certain quantitative data), so that the plausible space is constrained to a predefined shape, within which any movement will follows some suitable strategy.
The evaluation function can be applied to any plausible point in order to produce risk assessment and a discussion of the possible interventions.
It has to be stressed that shallow and deep knowledge are not synonymous of qualitative and quantitative knowledge (e.g. a deep structural model can be based on shallow attributes, or a numerical (deep) behaviour can be applied to a simple (shallow) structure.)
A simplified hierarchy of the structure itself is shown in figure 5. At the simplest level the structure assumes the form illustrated in figure 6; at a second level the structure is modelled according to what is represented in figure 7, where the "building" is decomposed into simpler objects describing his parts and the relations between parts; at deeper levels other decompositions have to be operated (e.g. a wall might be seen as an assemblage of vertical cantilevers and lintels and subsequently as an assemblage of bricks and mortar).

A behaviour hierarchy is associated to the object "building".
A hierarchy that can be used is shown in figure 8; again each level is subdivided into sublevels (qualitative and quantitative), where a major rôle is played by the constitutive relations used to model each element. Choices of primary importance are related to linearity and isotropy, static or dynamic simulations, damping, strain rate effects, unloading, stiffness and strength degradation, energy dissipation, failure criteria.

Attributes may be associated to objects at any level of the structure; some of these are automatically inherited by subobjects when a movement along the structure axis takes place (see figure 4). An example of a hierarchy of attributes for the object "wall" is given in figure 9; the first four levels apply to the building as a whole, too.
From the point of view of the constraints in the combination of different levels along the three axis some examples are given in what follows.

- For a representation of the structure at level one only the first and second behaviour level are applicable and only global attributes can be used.
  An example of such attributes are given in [6] (first level form), where they are all qualitative and coming from visual inspection.
- For a structure at level two a qualitative simulation of the elements can be combined with a computation of the shear strength on the base of global attributes, but it is possible to move along the attributes axis by asking detailed geometrical information or some experimental evaluation of the shear strength. On the behaviour axis four to seven levels (referred to figure 8) might be suitable depending on the attributes level.

6. The evaluation function

The fundamental approach followed in the risk assessment is the separation between simulation and evaluation.

The simulation activity covers the job of applying a seismic event to a building model (a point in the space in figure 4) to produce a possibly damaged model. This can be done for instance by a finite element simulation with a time history input, but also by a set of empirical rules which can produce qualitative damage on the base of qualitative attributes. An example of such rules are given in figure 10.

The evaluation activity is more complex, because it has to give a judgement on the output of the simulation activity.
This implies some definition of undesirable states, some definition of the distance between the present state and such limit states, some translation into economical values of such distances (social, historical, moral considerations are influencing this translation).
The evaluation has therefore to be performed through the following steps:

- simulating a seismic event, with the effect of generating new values of attributes;
- giving a judgement on the resulting damage, in a gravity scale;

1. rigid body

2. one degree of freedom (DOF)

3. one DOF per storey
(rigid floors)

4. three DOF per storey
(rigid floors, space structure)

5. walls and floor simulated by
macro elements

6. walls simulated by finite elements,
rigid floors (or macro elements)

7. walls and floors simulated by
finite elements

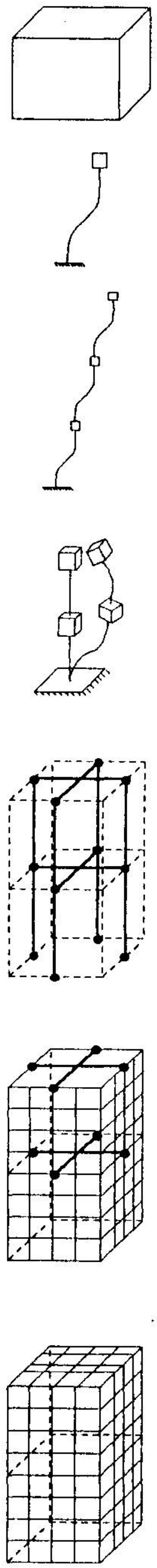


Fig. 8) The hierarchy of the behavioural models

1. Quality of the walls
2. Quality of the walls + total area
3. Total area + estimation of strength
4. Total area + experimental evaluation of strength
5. Geometry of each wall + estimation of strength
6. Geometry of each wall + experimental evaluation of strength

Fig. 9) Example of hierarchy of attributes

•	IF	good connections between walls
	THEN	<u>no damage expected</u>
•	IF	bad connections between walls
	AND	good connections between walls and floors
	AND	stiff floors
	THEN	<u>no damage expected</u>
•	IF	bad connections between walls
	AND	good connections between walls and floors
	AND	flexible floors
	THEN	<u>possible damage to the wall due to out of plane bending</u>
•	IF	bad connections between walls
	AND	bad connections between walls and floors
	AND	stiff floors
	THEN	<u>possible failure of floors</u>

Fig. 10) Example of qualitative simulation rules

- giving a judgement on the safety level (distance), in a safety scale, taking into account the attributes of the social-economical system;
- discussing the judgements on the base of the causal mechanism which generated them. The discussion is obtained going backward in the simulation.
  The discussion is important either to make possible to a human expert to check the "way of thinking" of the expert system and to give elements for another discussion, addressed at the next point;
- suggesting possible interventions, with their approximate (average) cost, using suitable bases of knowledge.
  The need of interventions is also discussed by comparing their cost with the cost of the expected damage, in terms of cost of repairing.
  It has to be kept in mind that different costs of retrofitting interventions might correspond to the same level of expected damage (depending on the damage mechanism).

7. The planner

The planner has two main functions, the first one related to the use of the artificial world "m", the second one related to the general strategy of the activities.

It has already been discussed that for a certain level of the model it is possible to evaluate the expected damage, the seismic risk and the cost of possible intervention.
It is obviously possible to obtain a more refined evaluation of all of them by new inspections, and/or experimental and/or numerical tests, but any possible refinement has a cost which can be quantified by entering the appropriate base of knowledge. Therefore the problem consists in deciding what is the benefit obtainable from a deeper knowledge in terms of probable reductions in the cost of the retrofitting interventions.
The main concept is that at a poor knowledge level the worst possible situation has to be adopted as true. On this base there is the probability that an increment of knowledge may allow a lighter intervention. Therefore the probable economical saving which can be obtained (evaluated by running again the simulation with a different starting situation) has to be compared with the cost of the new knowledge.
In conclusion the use of the artificial world "m" is governed by the principle of minimizing the probable total cost.
A secondary but important activity within this function consists of giving suggestions on the more suitable behaviour models depending on the available data (geometry, materials, stiffness, mass, connections, ...).

The second function has the purpose of suggesting the best strategy to be followed on the whole depending on objectives of the survey, budget, and again available data (number of buildings, expected damage, computed risk, ...). Clearly the strategy may be modified at each step of the procedure.
An example of a simple initial strategy might be as follows:

1. to perform a survey of all the buildings, getting only qualitative attributes;
2. to run simulator and evaluator using structure and behaviour at the simplest level;
3. to neglect the buildings with very low and very high risk for future testing (the meaning "very low" and "very high" depends on the budget);
4. to get more information for the other buildings;
5. to generalize information;
6. to run simulator and evaluator at deeper levels;
7. to choose the buildings on which it is more convenient to get more information on the basis of cost/benefit evaluation (the number of the buildings depends on the budget);
8. to repeat steps 4 to 7 until a certain level of reliability of the evaluation is reached or until no more funds are available;
9. to generate the final output.

8. Software engineering and development of the system

The system resulting from what has been previously described is a complex hybrid system, in which some parts are based on classic software techniques and some other are based on artificial intelligence techniques.
The problems in designing, developing and documenting such system are not different from the problems usually faced in software engineering.
The main choices for the development of the system have been as follows:

- the development process is based on step by step iterations on a prototype, with a series of phases for each step;
- at each iteration some chapter of a project file is generated or updated; all the documents related to the project are collected within the file.

The main chapters are:

- definition and modelling of the context of use of the system
- definition of the objectives
- modelling of the system with respect to the problem (independently on the implementation)
- translation into the implementation environment
- implementation
- evaluation

It has to be underlined that the modelling of the system does not depend on the specific knowledge representation techniques of the expert system shell that will be used. It is only in a second stage that the system model is translated into the specific languages (e.g. frames and rules).
A hypertext on a workstation will be the CASE environment for generating and updating the project file.
Petri nets are the base technique used to model the system; other techniques are used within the nets.

9. Conclusions

The system described is under development. A prototype which includes the building model, the evaluation function and the planner has been completed, so that risk evaluation and discussion of the possible retrofitting interventions are obtainable.
The system has been developed using the formalism of objects and rules supported by the shell Nexpert Object, on a SUN workstation with UNIX and on VAX station with VMS.
The prototype is being tested on the results of a survey on more than fifteen hundreds buildings, which has been originally performed on the base of the procedures proposed in [7,8].

10. Acknowledgments

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