KNOWLEDGE MANAGEMENT SUPPORTING DECISION MAKING IN HOLISTIC BUILDING RENOVATION DESIGN

Thorel Mathieu, PhD Candidate, mathieu.thorel@cstb.fr
Andrieux Franck, PhD, franck.andrieux@cstb.fr
Centre Scientifique et Technique du Bâtiment, Sophia Antipolis, France

Buhe Catherine, Professor, catherine.buhe@univ-savoie.fr
Laboratoire d'Optimisation de la Conception et d'Ingénierie de l'Environnement, Université de Savoie, Le Bourget du Lac, France

ABSTRACT

As retrofitting is a complex process where decisions can no longer be taken in isolation, there is an obvious need to invent new concepts forsons, CSTB aims to provide a comprehensive methodology, sustained by a set of knowledge-based tools, allowing a comprehensive understanding and assessment of the impacts of design decisions for retrofitting in order to implement the best combinations of energy-efficient building components.

This methodology relies on the establishment of a set of logical rules that expresses the functional dependencies between renovation components and the existing building. Such an expert knowledge will be modelled and used as Bayesian networks to take into account decision uncertainties under probability theory. Renovation packages generated by these networks will be ordered by a multi-criteria decision method, able to manage uncertainty, such as ELECTRE III.

Keywords: energy building renovation, multicriteria decision-making, knowledge management, design process, ICT.

1. INTRODUCTION

Precise assessment of energy performance for a renovation project is a complex process due to numerous uncertainties related to building characterization phase. Vagueness, ignorance and missing information are mainly due to the lack of traceability on implemented material and components, ageing of these components and users' behaviour model. These points contribute to the development of an uncertain environment that characterize renovation projects. Considering current practices, the lack of management of uncertainty on input data used to assess performance indicators can partially explain the difference between the calculated performance (simulation) and effective performance measured at delivery [WIT 02]. Sometimes the computed performance variations between two considered renovation solutions, is lower than the margin of error (known or not) on indicators values used to assess this performance. So, considering or not uncertainty may significantly influence the decision process.

Through this article, we intend to show a decision making methodology dedicated to the early phase of "light" building renovation design. The originality of this methodology consists in integrating uncertainty associated to decision process (characterisation of existing building, guided choice of renovation's solutions…). This uncertainty is propagated on quantitative performance indicators (energy consumption, life-cycle costing, environmental footprint), as well as qualitative indicators (comfort, health, usage).

Our research methodology is built on 7 elementary steps as followed:

- Definition of owner's needs, constraints and objectives (preferences) as well as site's constraints (external constraints);

- Holistic approach through a set of assessment indicators (at both building and compounds scales);
- Typological studies and sensitivity analysis on energy simulation model;
- Organisation and multicriteria characterisation of settled/renovation components;
- Guided extended diagnosis of initial situation (multicriteria assessment);
- Expert knowledge modelling (functional dependencies: utility functions, risks, constraints, opportunities…);
- Multicriteria decision making assistant in uncertain environment (sorting and ranking under user preferences).

The following section describes the various modules that compose this methodology and that will be merged in a fully operational process. The stress will be put on modules that show an innovative way of managing uncertainty in the decision process.

2. DESCRIPTION OF SCIENTIFIC MODULES

2.1 Module 1 performance indicators

Our systemic and multicriteria approach relies on a set of indicators (table 1) that allows to assess each facet of a renovation project. A part of these indicators is quantitative and based on variables such as output from calculation tools (estimate of annual energy consumption, life-cycle costing, environmental footprint); the others are qualitative, based on observation and modelling of building’s specialists expertise (comfort, social impacts, health, security, usage quality, resulting risks and pathologies). The performance assessment is estimated on a relative way, that is to say the efficiency of a renovation solution is calculated by comparison with the initial situation. This module «performance indicators » is composed of all the indicators defined and used in various CSTB’s research projects.

Table 1 :- Performance indicators

Energy demand		**Life Cycle Cost**		**Environmental footprint**			**Comfort assessment**			**Social impacts**				**Health**			**Usage quality**			**Risks**		
Annual energy consumption	Renewable energy consumption ratio	Investment costs	Operating costs	Total energy consumption	Total waste	Resources depletion	Thermal comfort	Acoustic comfort	Lighting comfort	Implementation time	Intensity of renovation in occupied site	Aesthetic aspect modification	Gross living area modification	Fresh air ratio	Asbestos presence	Radon Exposure	Accessibility	Protection against intrusion	Easiness to use	Loss of energy improvement potential	Moisture pathologies	Risks arising from combustion

2.2 Module 2 refurbishment stakes for residential buildings

Overall performance is a subjective concept that may be differently interpreted according to the decision-maker preferences. In most cases, these preferences are not clearly defined. In order to deal with this fact, we suggest to convert main refurbishment stakes (selected from the table 2), which are entry-points of refurbishment projects, into “influence points” assigned to our set of indicators, used to assess overall performance of our potential rehabilitation alternatives. This assignment should be made by specialists (HVAC engineer, acoustician, …) who analyzed what main and side effects can be attributed to specific stakes (for example, the main purpose of replacing heating system can be the increase of winter thermal comfort, but one potential collateral effects is the increase of interior noise associated to some technologies as heat pumps or air conditioners). These "influence points" are defined in a matrix crossing main stakes (rows) with indicators (columns). To each couple "stake / indicator" corresponds a specific number of influence points (0 for no influence, 1 for marginal influence, 2 for moderate influence, and 3 for first order influence).

This matrix is combined with the AHP method (Analytic Hierarchy Process) [SAA 80] used to weight the importance of stakes selected by a decision-maker to define his refurbishment project. By this weighting method, the "influence points" assigned to the selected stakes are weighted, after we add then normalize "weighted influence points" related to each indicator column. Using this method, we obtain the level of minimum performance wished on each indicators defined in order to identify or assess potential refurbishment alternatives. These target values on performance indicators are gathered in a vector, called hereafter PTV (Profile Target Values) which will be used to (1) identify efficient rehabilitation alternatives and (2) to ranking alternatives by preferences order.

Table 2:. Part of the main stakes associated to dwelling renovation projects

Main objectives	**External constraints**
Reduction in energy operating costs	Respect with the budget envelope
Replacing defective equipment or thermal envelope component	Respect of deadlines and possibility to renovate in occupied site
Resolving house disorders (water condensation, fungal growth…)	
Comfort improvement	
Increase gross living area	
Building modernization	
Environmental responsibility	
Compliance with regulations	

Table 3. ***Part of the main stakes associated to dwelling renovation projects***

2.3 Module 3 Characterization of existing situation

In order to help and simplify an extended diagnosis of existing situation and quantify uncertainty on input data, it was mandatory to carry out a preliminary work. This work concerned 3 axes:

1. Typological studies that have been realized on dwellings built between 1945 and 1974. These studies allowed to identify the granularity of available information required to perform an energy diagnosis. Depending on data such as the constructive mode, the year of construction, the surrounding urban density and the geographical area, some technical and generic solutions (envelope elements, energy equipment) have been identified to help the characterization of existing situation. This work allowed both the establishment of a multicriteria knowledge base of solutions, with filter-attributes such as « year of construction » or « geographical area », as well as the definition of a check-list used to fill-in dwelling technical specificities during technical diagnosis (pathologies potentially observed, air infiltration path …).

2. A multicriteria knowledge base of technical and generic solutions, already used in existing building or planned for renovation purpose, has been built. This helps us to structure information collected from various sources (typological and statistical studies, experience feedback, existing databases) and to make it usable in a decision-making tool that manage knowledge uncertainty. Renovation technical solutions used in our process have been divided into two lots: solutions related to the envelope and solutions related to energy systems. These lots are split up into 11 functional approaches and 34 technical solution families. Each technical solution is defined by a unique set of attributes, for which, values can change in a predefined perimeter (constituting a variant of the same technical solution). Figure 1 explains this organisation with a practical example: the case of *cladding system* belonging to the *external wall insulation* family.

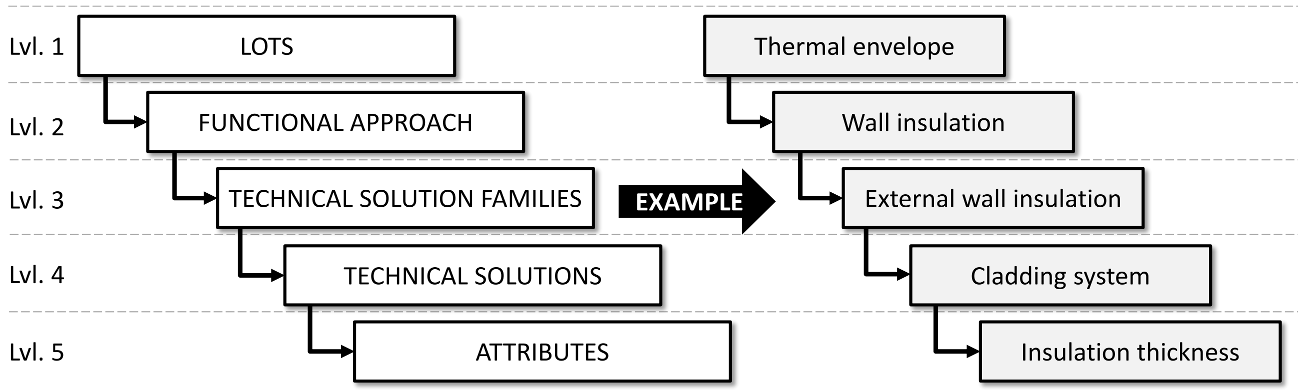


Figure 1: Functional decomposition of rehabilitation technical solutions

To each solution are associated different kinds of attributes: those who are common to all solutions (initial cost, implementation time, environmental footprint, estimated lifespan…), those who are energy simulation oriented (specific input data used by calculation cores), and those oriented to decision process (implementation constraints, multicriteria performances). Uncertainty on attribute numerical values attached to technical solutions is coded, in the best case as a probability distribution, and in the other cases as uniform or triangular possibility distribution defined by expert judgments (minimal value : x_{min}, most representative : X_{pp}, maximal value : X_{max}) (Figure 2).

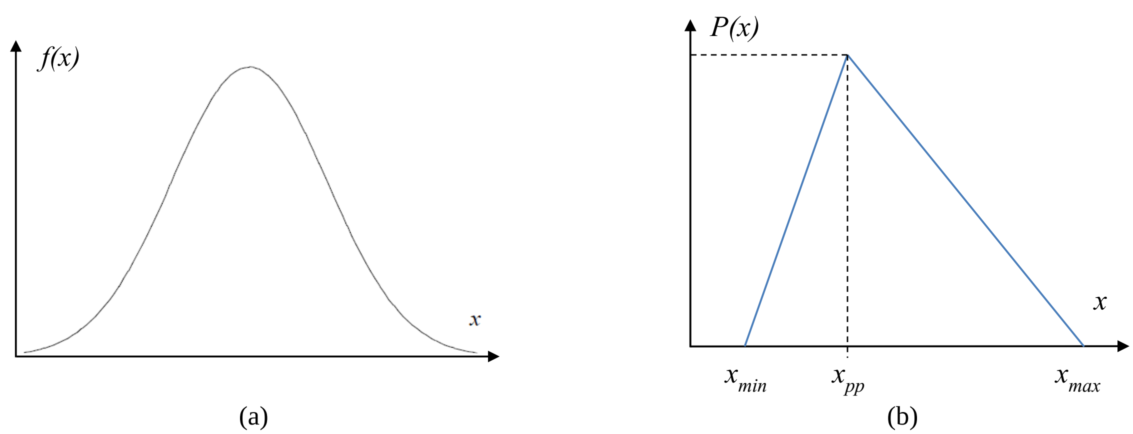


Figure 2: (a) Gaussian probability distribution (normal shape). (b) Triangular possibility distribution

3. For some dwelling typologies, sensibility and uncertainty analyses have been carried out, using a dynamic thermal simulation tool, in order to identify the physical data that are the most influent on energy performance assessment. These analyses have been conducted with Morris Screening and then Monte-Carlo methods [WIT 02]. A guided procedure has been implemented to determine sensitive data such as windows solar factor or surface heat transfer coefficient of walls, in order to avoid intrusive sounding (core sampling) or expensive measures (thermography), and then quantify these uncertainties. These procedures target to reduce uncertainty on data that have a strong impact on performance assessment.

These preliminary works allow us to implement a guided diagnosis feature which is an essential step to assess the potential energy increase and identify the most relevant and compatible technical solutions for specific building. We recommend a 3 step diagnosis:

1. Subjective assessment of comfort indicators through surveys provided to occupants, as it is made in EPIQR tool [BLU 00]. The following performance indicators are evaluated: winter thermal comfort, summer thermal comfort, acoustic comfort, natural light access level, olfactory comfort and accessibility.
2. Envelope pathologies and chronic discomforts identification (optional step): in case envelope pathologies are observed (e.g. traces of moisture) or chronic discomforts are noticed, a set of additional questions, from the

most general to the most specific, are asked to the occupant in order to identify the most probable causes of these annoyances. The idea is to carry-out an energy renovation design, well adapted to each situation.

3. Monitoring of a technical check-list: during the dwelling visit, the person in charge of the diagnosis determines the input values (or ranges of values when the information is uncertain) required to assess the energy performance. During the same visit, this person fills in a technical check-list in order to take an inventory of technical, architectural and regulatory constraints applied to the project.

2.4 Module 4 expert knowledge modeling

Through the literature, many experience feedbacks on former refurbishment projects allow us to identify best practices to follow in order to improve overall performance on existing residential buildings [POU 10] or to design low energy buildings [RAG 12]. However, the integration of these practices into an automatized process to help choose rehabilitation solutions, remains marginal: few tools explain to professionals if advocated solutions are compatibles with the building characteristics and the decision-maker preferences or not.

Our objective is to propose an integration of this expert know-how, in a probabilistic inference model based on Bayesian approach [NAI 07 ; HAN 08].

During our collect of energy rehabilitation know-how, we have highlighted 5 categories of expert rules:

1. *technical constraints*: technical prerequisites for the implementation of rehabilitation solutions due to building specificities (potentially technical incompatibilities);
2. *regulatory constraints*: regulatory prerequisites for the implementation of rehabilitation solutions (or packs of solutions) due to building specificities (potentially regulatory incompatibilities);
3. *utility functions*: impact functions (assessing qualitative indicators) related to the implementation of rehabilitation solutions (primary and side effects – either positive or negative effects);
4. *risks involved or resulting pathologies*: special utility functions defining risks of strong occupant dissatisfaction (or sanitary pathologies) following a specific "building-solutions" configuration;
5. *opportunities for coupling with maintenance actions*: combination of scheduled maintenance action with a technical solution family of rehabilitation to reduce costs or delays in implementation (example : external wall insulation + facade facelift = reduction of labor costs).

These rules may be applied to different level of functional description of a rehabilitation solution (Figure 1), and impact performance indicators at different scales (building or solution). Both first categories affect implementation conditions of rehabilitation solutions, others act on impacts resulting from this implementation on a building with his specificities and the way people live in it. Impacts are modeled as a modification of the initial level on performance indicators.

Bayesian networks (BNs) are tools for modeling discretized uncertain knowledge (partial data, inaccuracy). BNs are probabilistic models with two components:

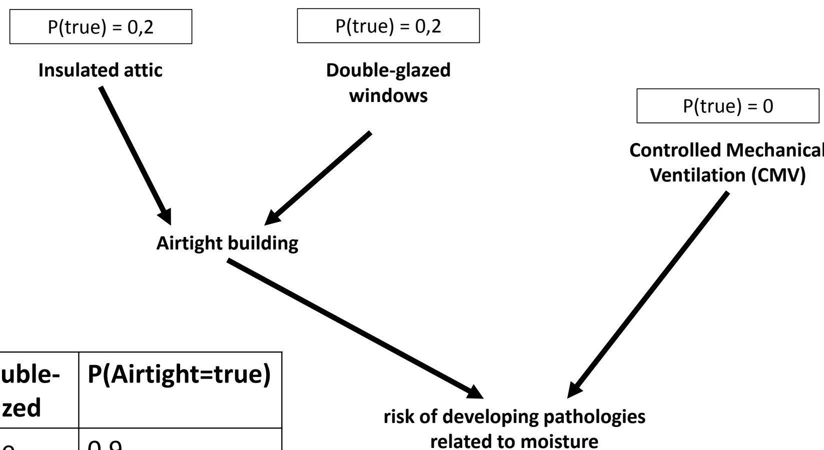
- a qualitative component, representing independence relations by directed acyclic graph (DAG), where each node Xi represents a variable and each arc represents the relationships between these variables;
- a quantitative component, representing the uncertainty of the relationships between variables, with each variable Xi associated with a conditional probability table (CPT) containing the variable probabilities of being in a given state given its parents' states (pa_i). The joint probability distribution for X = { X1, X2, …, Xn } is given by the chain rule:

$$P(X_1, X_2, ..., X_n) = \prod_{i=1, ..., n} P(X_i \mid pa_i)$$

Probabilistic inference allows to compute the probability of any variable, given observed variables. BNs inference is based on the notion of propagating evidence [DEL 12]. BNs can be used to perform abductive reasoning (i.e., diagnosing a cause given an effect) and deductive reasoning (i.e., estimate an effect given a cause). Applied to rehabilitation process, this probabilistic approach allows a buildings specialist to assess different qualitative states of a performance indicator, given available observations (from a diagnosis) and his own knowledge (expert rules transcribed in CPT). Constraints rules can also be coded as Boolean relationships between technical solutions and dwelling specificities.

An example will be taken to facilitate understanding of the inference process in Bayesian networks. The diagram presented in Figure 3, assesses the probability of seeing an effect (developing pathologies related to moisture) as a function of a combination of potential observations (attic insulation, exterior joinery, ventilation system). The more the observations are checked, the more the deductive effects can be sure, and vice versa. Uncertainties related to dwelling knowledge can be integrated in Bayesian model, under the shape of *probability distributions* of observations and *CPT* [NAI 07].

BN technology allows knowledge inference by mixed chaining (forward and backward chaining). Applied to rehabilitation process, the first type of reasoning helps to design efficient technical solution combinations considering data collected *during rehabilitation stakes selection* and *initial diagnosis* (respectively modules 2 and 3), the second helps the diagnosis step by finding the most probable causes of an observed effect.



Insulated attic	Double-glazed	P(Airtight=true)
true	true	0,9
true	false	0,3
false	true	0,65
false	false	0,1

Airtight building	CMV	P(Risk=true)
true	true	0,01
true	false	0,7
false	true	0,1
false	false	0,3

Figure 3: Simplified theoretical modeling of a Bayesian network coding the probability of developing pathologies related to moisture in a dwelling[1]

Applied to our methodology, conversion of expert rules – *expressed under the shape of logical functions* – in CPT, connecting *Bayesian nodes* representing either technical rehabilitation solutions, or performance indicators, or building specificities), allows to build compatible combinations of technical solutions (i.e. alternatives) that answer to refurbishment stakes potentially selected in Module 2.

2.5 Module 5 : Decision-support assistant

Our decision-support assistant operates in a two-step approach. The first step involves generating rehabilitation alternatives (i.e. combination of one or more technical solutions) thanks to Bayesian networks. The second step consists in categorizing and hierarchizing alternatives newly designed in order to satisfy decision-maker preferences thanks to multicriteria decision methods ELECTRE (TRI then III).

[1] This diagram is an application example, the conditional rules expressed have not been checked by Indoor Air Quality specialists

2.5.1 Assisted generation of rehabilitation alternatives

We define two classes of Bayesian networks.

The first class, composed of a unique network, gathers technical solution families (Figure 1). In this network, two main types of nodes exist : performance indicator nodes (modeled as utility node : each discretized value represents a qualitative level of performance – *e.g. "excellent, good, medium, low"*) and functional approach nodes (modeled as observation node : each discretized value represents a technical solution family answering the same functional approach – *e.g. families "external wall insulation, internal wall insulation, cavity wall insulation" for the functional approach "wall insulation"*). The use of this network allows to target technical solution families that address refurbishment stakes through PTV defined in Module 2. It facilitates the identification of families' combinations to recommend (i.e. pulling up the values of the desired performance indicators) or otherwise to avoid (i.e. generating a risk).

The second class is composed of 34 independent networks, each related to one technical solution family. Here each network integrates the technical solutions belonging to the same family (as observation nodes) as well as more operational expert rules like implementation conditions of technical solutions (as observation nodes) or utility functions (as utility node) allowing the reduction of the choice uncertainty.

We elaborate rehabilitation alternatives as follows:

- Step 1: In the BN gathering all technical solution families.

  Step 1.a: We start to integrate constraints rules applied to a specific project (e.g. inability to undertake external wall insulation due to the encroachment of public road) then we impose target values from PTV by descending weighting order (computed in module 2) on the nodes representing performance indicators. By Bayesian inference, occurrence probability of each technical solution family in functional approach nodes are revised, in order to reach PTV on performance indicator nodes;

  Step 1.b: Then we scan the remaining possibilities and retain families approaching the desired performance (families with high occurrence probability).
- Step 2: For each identified technical solution family, the decision-maker decides if he gets sufficient information to take a decision or if he rather prefers refine his choice in reiterating 1.a and 1.b steps on each BN representing selected technical solution family. But this time, with the objective of identifying best technical solutions according to his preferences.

At the end of this second step, we automatically generate all combinations of selected technical solutions, and assess probability distributions on performance indicator nodes coded in BN. Each combination is hereafter called *rehabilitation alternative*. To assess other performance indicators (those quantitative), we test each alternative with available simulation tools (estimate of annual energy consumption, life-cycle costing, environmental footprint) by propagating uncertainties with Monte-Carlo Method.

2.5.2 Multicriteria ranking in uncertain environment

The number of alternatives generated can be substantial. For example, if 5 technical solutions, each owning 4 different sets of attribute values (e.g. thickness or raw material of an insulation panel), are highlighted by our model, 5^4= 625 alternatives are theoretically possible. Therefore, it is necessary to sort these potential alternatives to highlight those come closest to the decision-maker preferences (our PTV).

In order to reduce the number of alternatives to rank, ELECTRE TRI method [YU 92] is used to categorize these alternatives in function of their distance from PTV. For example the category "good" includes alternatives with performance indicator values upper than values from PTV, the category "medium" includes alternatives with performance indicator values between PTV and 80% of PTV and so on. Preference and veto thresholds, belonging to ELECTRE methods, allow consider uncertainties related to the assessment of performance indicator values (e.g. nominal value + uncertainty range, probability distributions) used as assessment criteria. Then we retain the best non-empty category which contains a reasonable number of alternatives to compare (< 100 items), next we use ELECTRE III method to rank by order of preference the retained alternatives. Through this last step, an ordered set of alternatives according to decision-maker preferences is proposed. This ranking tolerates equally placed alternatives [MAY 94].

3. ARTICULATION OF SCIENTIFIC MODULES

Figure 4 shows the articulation of scientific modules described above.

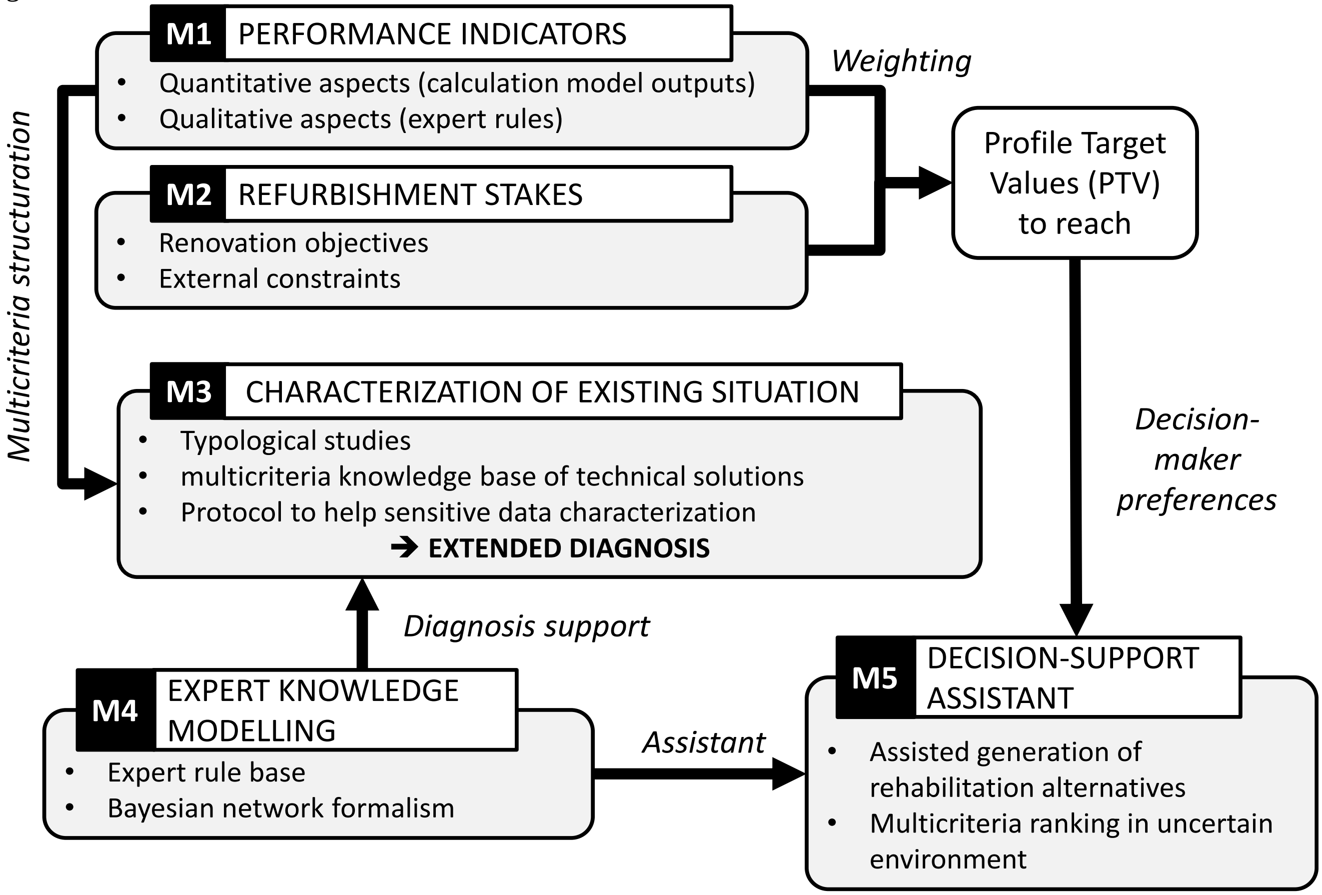


Figure 4: Articulation of scientific modules

CONCLUSION

The multicriteria decision making methodology that has been presented in this paper is on the way to be finalized. The main objective is to take into account uncertainties associated to characterization of existing situation and in the elaborating renovation alternatives process that we propagate to performance indicators used as decision criteria. Future articles are in progress and specifically target guided diagnosis and a detailed view of alternatives design process based on Bayesian networks. At the moment the methodology hasn't been applied in a practical case but we will soon have the opportunity to apply it to the renovation of real individual houses based in different places such as La Rochelle and Chambery. We will implement our methodology (end user side) in 4 different steps: (1) stakes definition, (2) extended diagnosis, (3) guided elaboration of renovation alternatives; (4) multicriteria ranking analysis of the most relevant alternatives among those who were assessed.

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