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Decision support methodologies on the energy efficiency and energy management in buildings

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Abstract

The aim of the present chapter is to analyse the decision support processes towards energy efficiency and improvement of the environmental quality in buildings. The main criteria in the decision analysis of buildings are categorized. The decision alternatives which may formulate specific actions, or group of actions (strategies) for buildings' sustainability are analysed. The decision methodologies presented are separated to online (based on real-time operation of buildings) and offline decision approaches. Both approaches are supported by simulation, multi-objective programming optimization techniques, multi-criteria decision analysis techniques and their combinations in order to reach optimum solution, rank alternatives or provide trade-offs between the criteria. The advantages and drawbacks of the various methods are discussed and analysed.

■ *Keywords* – energy efficiency; indoor environment; multi-criteria decision analysis; multi-objective decision support; energy management systems

INTRODUCTION

The building sector has a substantial share of the primary energy supply being a major contributor to conventional fuels consumption, thus creating a significant environmental burden through materials production and global warming gas releases. Buildings account for about 40 per cent of the global energy use. To save a significant portion of this energy, the International Energy Agency (IEA, 2008) recommends action on:

- building codes for new buildings;
- passive energy houses and zero energy buildings;
- policy packages to promote energy efficiency in existing buildings;
- building certification schemes;
- energy efficiency improvements in windows.

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The European energy policy has a clear orientation towards the preservation of energy and the improvement of indoor environmental quality in buildings through the adoption of the European Commission's (EC) Energy Performance of Buildings Directive (EPBD) 2002/91/EC (EC, 2003). To support EPBD, the Comité Européen de Normalisation (CEN) introduced several new CEN standards (e.g. CEN 2005; CEN 2006). The EC, on January 2008, unveiled the Climate Action package to fight climate change and promote renewable energy in line with European Union (EU) commitments. This builds on the many targets that the EU set itself in 2007 for 2020 as part of the Energy Policy for the EU, including 20 per cent reduction in greenhouse gases, 20 per cent increase in energy efficiency, and increasing renewable energy use to 20 per cent of the total energy consumption.

To this end, in the past decades, there have been significant efforts towards designing, operating and maintaining energy efficient and environmentally conscious buildings.

Optimal energy management and energy efficiency in the buildings sector is a valuable tool for natural resources conservation. Moreover, the financial benefits from using energy efficient technologies constitute the major motivation for building owners. Buildings' energy efficiency and environmental burden are treated differently in the design and operational phase. In selecting the most appropriate actions or strategies for energy efficiency and reduction of buildings' environmental impact, either in the design or in the operational phase, various methodologies are utilized.

The aim in the buildings' design or renovation phase usually is:

- compliance of the building with regulations in the design or in the operational phase;
- improvement of the building's energy efficiency in a sector (i.e. heating or cooling) or overall improvement;
- improvement of the indoor environment (i.e. improvement of indoor thermal comfort, visual comfort or indoor air quality or a combination of these);
- environmental impact of the building for global warming, etc.;
- reduction of the energy-related costs.

More specifically, in the design phase, the objective is to achieve the best equilibrium between the essential design parameters versus a set of criteria that are subject to specific constraints. The essential design variables that contribute to the energy and environmental burden of a building and influence the occupants' comfort, the heating and cooling energy demand as well as the lighting demand can be (Gero et al, 1983):

- building shape;
- orientation;
- building mass;
- type of glazing and glazing ratio;
- shading.

Usually, the designer uses simulation building modelling to assess predefined design aspects and solutions, subject to the building owner's subjective preferences (cost of the building, energy efficiency, aesthetics, etc.).

In the operational stage of a building, decisions towards energy efficiency are usually undertaken with the support of energy audit and survey procedures (Krarti, 2000). Energy auditing of buildings can range from a short walk-through survey to a detailed analysis with hourly computer simulation. Any actions in the building undertaken during its operational stage can be either refurbishment or retrofit. The term refurbishment implies the necessary modifications in order to return a building to its original state, while retrofit includes the necessary actions that will improve the building's energy and/or environmental performance.

The state of practice procedure for the improvement of a building's energy efficiency in its operational phase follows four steps:

- Step 1: Buildings analysis. The main purpose of this step is to evaluate the characteristics of the energy systems and the patterns of energy use for the building. The building characteristics can be collected from the architectural/mechanical/electrical drawings and/or from discussions with building operators. The energy use patterns can be obtained from a compilation of utility bills over several years. Analysis of the historical variation of the utility bills allows the energy auditor to determine if there are any seasonal and weather effects on the building energy use.
- Step 2: Walk-through survey. Potential energy saving measures are identified in this part. The results of this step are important since they determine whether the building warrants any further energy auditing work. Some of the tasks involved in this step are:
  - identification of the customer concerns and needs;
  - checking of the current operating and maintenance procedures;
  - determination of the existing operating conditions of major energy use equipment (lighting, heating ventilation and air-conditioning systems, motors, etc.);
  - estimation of the occupancy, equipment and lighting (energy use density and hours of operation).
- Step 3: Creation of the reference building. The main purpose of this step is to develop a base-case model, using energy analysis and simulation tools, that represents the existing energy use and operating conditions of the building. This model is to be used as a reference to estimate the energy savings incurred from appropriately selected energy conservation measures.
- Step 4: Evaluation of energy saving measures. In this step, a list of cost-effective energy conservation measures is determined using both energy saving and economic analysis. A predefined list of energy conservation measures is prepared. The energy savings due to the various energy conservation measures pertinent to the building using the baseline energy use simulation model are evaluated. The initial costs required to implement the energy conservation measures are estimated. The cost-effectiveness of each energy conservation measure using an economic analysis method (simple payback or life cycle cost analysis) is assessed.

Regardless of the dwelling's phase (design or operational), energy efficiency and sustainability in buildings is a complex problem. This is attributed mainly to the fact that buildings consist of numerous subsystems that interrelate with each other. The subsystems are:

- structural system and materials;
- building systems, like heating, ventilation, air-conditioning and lighting;
- building services, such as support of indoor comfort requirements and management.

Therefore buildings' sustainability is reached by taking the necessary decisions that are optimum for the overall system. This implies a decision support approach with the following steps:

- identification of the overall goal in making a decision, subsidiary objectives and the various indices or criteria against which option performance may be measured (objective function);
- identification of the alternative options or strategies;
- assessment of each option and/or strategy performance against the defined criteria;
- weighting of objectives or criteria;
- evaluation of the overall performance;
- evaluation and ranking of options;
- sensitivity analysis.

The purpose of the present chapter is to analyse the state of the art of the methodologies for decision support in energy management and sustainability for the building sector. The steps usually followed in this procedure and listed above are depicted in Figure 5.1. The first major step is to find the overall goal and criteria based on which the process will be assessed. The main criteria and objectives in the state of the art are analysed in 'Criteria in Decision Support for Energy Efficiency and Energy Management' below. The actions usually undertaken by the designers, architects, building scientists, etc. are presented in 'Alternative Options and Strategies'. 'Assessment methodologies' analyses the assessment methods for buildings' energy and environmental improvement, while the decision support methodologies are discussed in the following section. 'Conclusion and Future Prospects' summarizes the main conclusions of the chapter and highlights further development needs.

CRITERIA IN DECISION SUPPORT FOR ENERGY EFFICIENCY AND ENERGY MANAGEMENT

The criteria for energy efficiency and energy management in a new construction or retrofit can be either quantitative or qualitative and can be divided into the categories depicted in Figure 5.2.

More specifically, regarding *energy use* (primary or delivered), the following indices have been utilized in chronological order:

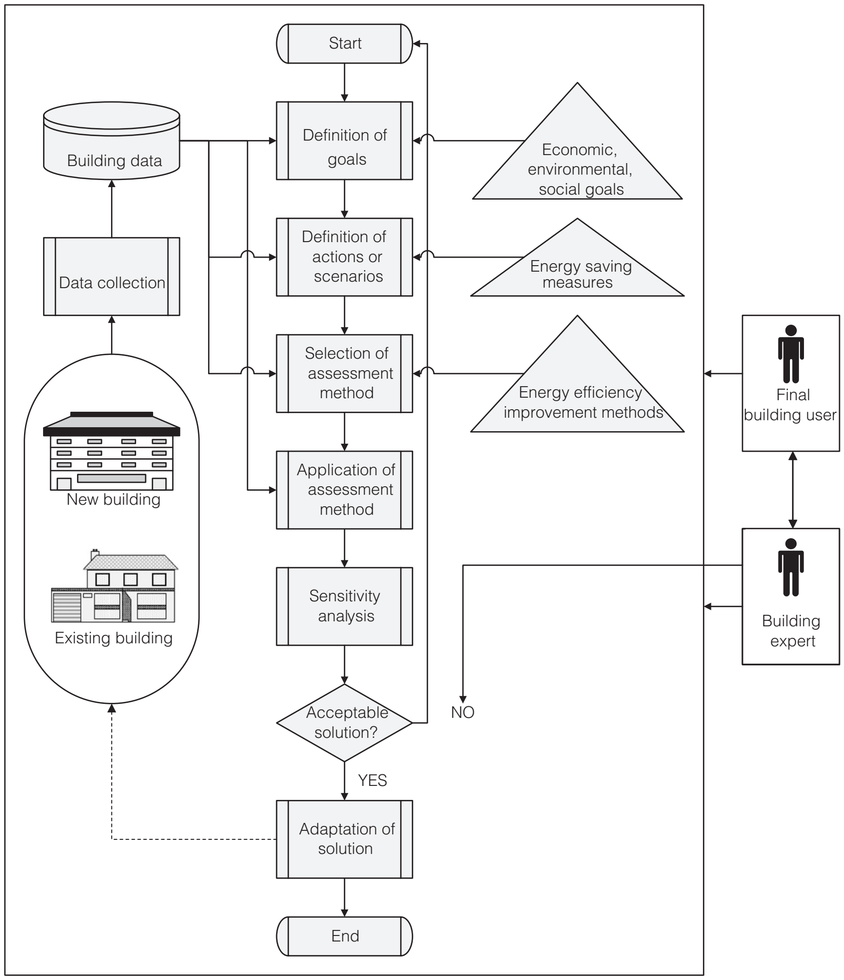

FIGURE 5.1 The methodology for buildings' design and operational improvement

- heating and cooling load for conditioned buildings (D'Cruz and Radford, 1987; Bouchlaghem, 2000);
- normalized annual energy consumption and energy use for heating in kWh/m^2 (Rey, 2004; Zhu, 2006);
- annual electricity use in kWh/m^2 (Rey, 2004);
- embodied energy (Chen et al, 2006);
- energy and time consumption index (ETI) (Chen et al, 2006);
- energy savings by retrofitting expressed by $\left(1-\frac{\text{Energy}}{\text{Energy baseline}}\right)\%$ (Gholap and Khan, 2007).

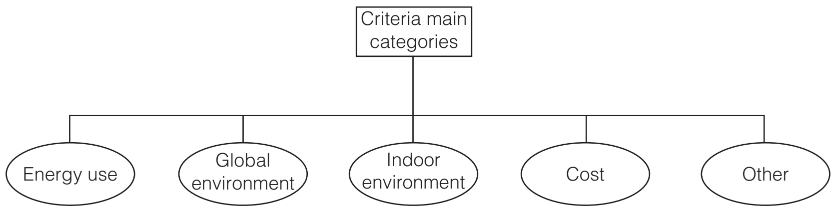

FIGURE 5.2 The main criteria for energy efficiency and environmental quality in the building sector

Regarding *costs*, the following indices have been found in the literature:

- direct costs and initial investment costs (Rosenfeld and Shohet, 1999);
- economic life span (Rosenfeld and Shohet, 1999);
- annual ongoing maintenance charges (Rosenfeld and Shohet, 1999; Rey, 2004);
- annual ongoing charges (Rey, 2004);
- net present value (NPV) of the energy investment (Martinaitis et al, 2004);
- internal rate of return (IRR) of the energy investment (Martinaitis et al, 2004);
- cost of conserved energy (CCE) (Martinaitis et al, 2004);
- life cycle cost (LCC) (Wang et al, 2005);
- cost of retrofitting expressed by $\left(1-\frac{\text{Energy}}{\text{Energy baseline}}\right)\%$ (Gholap and Khan, 2007).

As far as *global environment* is concerned, the criteria usually set are:

- annual emissions GWP (global warming potential in $kg_{eq}CO_2/m^2$) (Rey, 2004);
- reduction potential of global warming emissions (Alanne, 2004);
- life cycle environmental impact (Wang et al, 2005);
- acidification potential in $kg_{eq}SO_2/m^2$ (Rey 2004; Alanne et al, 2007);
- water use (Alanne et al, 2007).

Indoor environmental quality and *comfort* have subcategories for the evaluation of thermal sensation, visual comfort, indoor air quality and acoustic comfort. More specifically, regarding *thermal comfort*, the following criteria and indicators have been used:

- predicted mean vote based on ISO 7730 standard (ISO, 1984);
- dry resultant temperature for unconditioned buildings (Bouchlaghem, 2000);
- indoor temperature and humidity (Jaggs and Palmer, 2000);
- discomfort hours during summer or winter (Roulet et al, 2002);
- daily overheating in K (Rey, 2004);
- percentage of people dissatisfied index (Blondeau et al, 2002; Rutman et al, 2005);
- effective draught temperature index (Rutman et al, 2005);
- summer thermal discomfort severity index, which indicates the summer severity of excessive mean radiant temperature during summer (Becker et al, 2007).

For *visual comfort*, the assessment criteria can be:

- daylight availability (Radford and Gero, 1980);
- lighting and visual comfort (e.g. EPIQR method, see Bluyssen, 2000; Rey, 2004);
- daylight factor (Rey, 2004);
- discomfort glare severity indicator, which indicates the annual severity of excessive discomfort glare (Becker et al, 2007).

Indoor air quality can be assessed via:

- CO_2 concentration index (Kolokotsa et al, 2001; Doukas et al, 2007);
- maximum ratio between the mean concentration of a contaminant over the occupancy period and the contaminant's threshold limit value for short-term or long-term exposure (Blondeau et al, 2002);
- ventilation rates (Blondeau et al, 2002).

Acoustic comfort criteria include:

- noise level in dB at workplace (Rey, 2004);
- noise rating index (Rutman et al, 2005).

Other criteria for assessing buildings' performance in conjunction with energy efficiency can be:

- construction duration (Rosenfeld and Shohet, 1999);
- level and ranking of the service according to state of the art (Rosenfeld and Shohet, 1999);
- uncertainty factors (Rosenfeld and Shohet, 1999);
- communication cost between spaces (Homoud, 2001);
- allocation of activities within spaces (Homoud, 2001);
- functionality (Alanne, 2004) influenced by:
  - easiness of implementation of the retrofit
  - effect on comfortability
  - space requirements
  - adaptability to existing structure
  - usability
  - serviceability;
- work efficiency of building energy management systems (BEMS) and intelligent buildings, such as reliability (Wong and Li, 2008);
- security, i.e. fire and safety features, alarm systems, etc. (Wong and Li, 2008).

Most of the aforementioned criteria are competitive. As a consequence, it is impossible to find a global solution to satisfy all of them simultaneously. For this reason, several decision support techniques are used in both the design and operational phases to enable reaching a solution that will be satisfactory enough according to the preferences and priorities of the building user/owner.

ALTERNATIVE OPTIONS AND STRATEGIES

The different actions that may be undertaken include more than 400 alternatives (Wulfinghoff, 1999) and may be grouped in categories as tabulated in Table 5.1. Moreover these actions may be accomplished separately or combined in groups thus formulating a strategy (see Table 5.1 and Figure 5.3). Additionally, all actions may be applied to both the design (Becker et al, 2007) and the operational phase (Alanne 2004).

The selection of actions for each building depends upon its characteristics, the scope of the retrofit or design and the criteria that the actions will serve. For example, a decision support approach for selecting energy-saving building components in the building design is proposed by Wilde and van der Voorden (2004). The alternative actions for this specific work include solar walls, advanced glazing, sunspaces and photovoltaic arrays. Additionally, the influence of building design variables and improvement of the ventilation schemes on the thermal performance, indoor air quality and energy efficiency is studied by Becker et al (2007). The alternatives selected are on the one hand related to the building's design, i.e. building orientation, size of windows, thermal insulation, mass, colour and facades and, on the other hand, to various ventilation schemes.

Lists of retrofit actions are provided by various researchers (Alanne, 2004; Doukas et al, 2008). Indicatively, these lists include:

- lighting improvements such as replacement of lamps and use of lighting control systems;
- heating and cooling improvements such as installation of extra monitoring devices, introduction of natural gas or solar energy systems for absorption cooling, etc.;
- electromechanical equipment improvements such as load factor corrections, etc.;
- general improvements, i.e. installation of renewables, insulation, etc.

An example of a set of alternatives in a strategic form is provided by Rosenfeld and Shohet (1999) including full retrofit, partial retrofit actions, demolition and reconstruction of the building and construction of a new building nearby.

Moreover, regarding strategies, i.e. combined actions that lead to a specific result, Rey (2004) proposes the following:

- the stabilization strategy (STA) which consists of a set of actions that do not alter the building's appearance;
- the substitution strategy (SUB) which consists of a set of actions that alter the building's appearance to a great extent;
- the double-skin facade strategy (DSF) which corresponds to adding a new glass skin.

As a general comment, all efforts for energy efficiency and improvement of building performance are focusing on specific actions or action categories without the adoption of a global and holistic approach mainly due to the problem's complexity.

TABLE 5.1 The different actions for improving buildings' energy efficiency

BUILDING COMPONENT	STRATEGY	ACTIONS	
Building envelope and design aspects	Increase of insulation	Roofs	Increase the quantity of attic insulation; add rigid insulation to the top surface of roofs; apply sprayed foam insulation to the top surface of roofs; Install a suspended insulated ceiling, etc.
		Walls	Insulate wall cavities; insulate the inside surfaces of walls; insulate the outside surface of walls, etc.
		Glazing	Install high-efficiency glazing; install storm windows or supplemental glazing; reduce the areas of glazing; install thermal shutters; use window films that reflect heat back into the building, etc.
	Reduction of air leakage	Install appropriate weather-stripping on exterior doors; install high-efficiency doors; maintain the fit, closure, and sealing of windows; install weather-stripping on openable windows; install supplemental ('storm') windows; install high-efficiency windows; seal gaps in the envelope structure, etc.	
	Use of advanced building envelope technologies	Spectrally selective glasses; chromogenic glazings; cool materials, etc.	
	Control and exploitation of sunlight	Reduction of cooling loads	Install external shading devices appropriate for each exposure of the glazing; install internal shading devices; install high-efficiency glazing; install solar control films on existing glazing; reduce the area of glazing (with insulating panels), etc.
		Daylight	Install skylight or light pipes; install diffusers for existing clear skylights; install translucent roof and wall sections for daylight; install diffusers to make windows more effective for daylight; install a system of light shelves and shading, etc.
		Passive solar heating	Keep open the window shades of unoccupied spaces that need heating; install combinations of sunlight absorbers and reflectors inside windows and skylights; install solar enclosures over areas that can benefit from heating, etc.

TABLE 5.1 The different actions for improving buildings' energy efficiency *(Cont'd)*

BUILDING COMPONENT	STRATEGY	ACTIONS
Building services	Heating Ventilation and Air-Conditioning Systems (HVAC)	Setting up/back thermostat temperatures; regular retrofit of constant air volume systems, etc; installation of heat recovery systems; retrofit of control heating plants, etc.
	Mechanical Equipment	Boiler types and ratings maintenance; use of Compression cooling; absorption cooling; variable-speed motors and drives, etc.
	Office equipment	Control of operating time, use of high-efficiency office equipment.
	Motors	Reduction of operating time; optimized control; Installation of energy efficient motors.
	Electric systems	High-efficiency lamps & ballasts; addition of reflecting devices; light pipe technologies; replace fluorescent lamps with high-efficiency or reduced-wattage types; replace ballasts with high-efficiency or reduced-wattage types, or upgrade both ballasts and lamps; install current limiters; install fluorescent dimming equipment; consider retrofit 'reflectors' for fluorescent fixtures, etc.
Energy management tools	Monitor and control of the building during its operation	Sensors; clock controls and programmable thermostats; measurement of liquid, gas, and heat flow; control signal pooling; energy analysis computer programmes; advanced control systems; decision support systems; energy management control systems, infrared thermal scanning, etc.

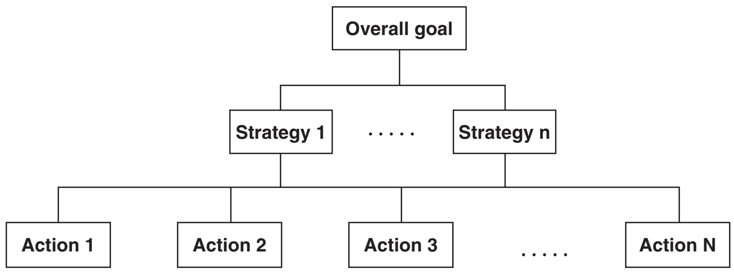

FIGURE 5.3 The actions and strategies tree

ASSESSMENT METHODOLOGIES

The decision problems are generally based on the description of the set of alternatives and can be (Ehrgott, 2005):

- Problems with a large but finite set of alternatives that are explicitly known. Usually, the goal is to select a most preferred one.
- Discrete problems where the set of alternatives is described by constraints in the form of mathematical functions.
- Continuous problems – the set of alternatives is generally given through constraints.

Finding the optimum decision is usually an optimization procedure. Optimization is a technique of maximizing or minimizing specific objective functions under constraints. The objective functions are formulated to represent the decision criteria. Therefore, the selection of the optimization procedure depends on the problem's particularities.

In the building sector, the assessment phase involves the evaluation of the predefined actions or strategies analysed in 'Alternative Options and Strategies' versus the selected criteria that have been pinpointed in 'Criteria in Design Support for Energy Efficiency and Energy Management'. Difficulties and drawbacks exist due to buildings' complexity (Homoud, 2001).

The major issues that arise are:

- The criteria are usually more than one and are conflicting (indoor comfort and energy, energy consumption and investment cost, etc.).
- The actions discussed in 'Alternative Options and Strategies' involve a number of decision variables that are not negligible.

Therefore, the assessment procedure is an iterative procedure strongly influenced by the criteria, the alternatives, actions and strategies and finally by the end user. This iterative procedure is illustrated in Figure 5.4.

The approaches towards the improvement of energy efficiency in buildings that are met in the relevant literature may be distinguished according to their different characteristics (Figure 5.5).

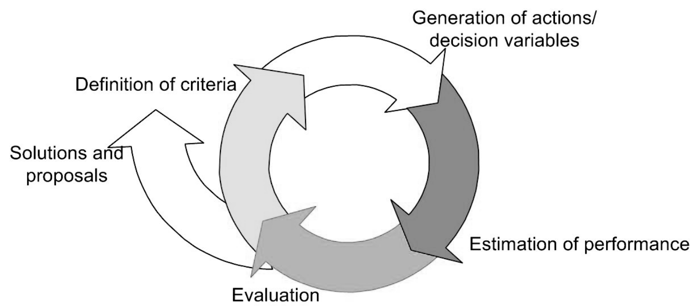

FIGURE 5.4 The iterative decision support process (Alanne, 2004)

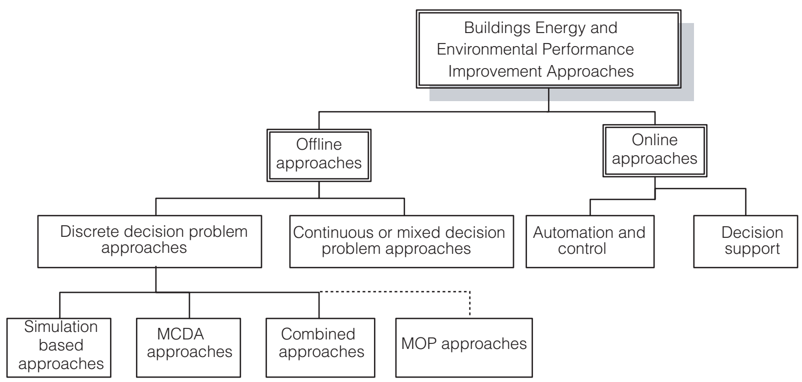

FIGURE 5.5 Categorization of methodological approaches for the improvement of energy efficiency in buildings

Depending on how an approach is implemented, they may be distinguished in offline and online approaches. Offline approaches aim to identify particular measures such as insulation materials, wall construction, boiler type, etc. that are expected to lead to improved building energy and environmental performance. These approaches may be applied either during the design phase or in the frame of a refurbishment or retrofit during the operational phase of the building. The offline approaches are not interacting with the building in real time. Online approaches, on the other hand, aim to identify particular parameters such as setpoints, control strategies (night setback, compensation, etc.) based on real-time measurements collected through a BEMS that improves the energy performance of the building during its real-time operation. Both online and offline approaches are analysed in the following sections.

OFFLINE APPROACHES

Offline approaches may be further divided into approaches that are applied to a decision problem formulated as a discrete one, and approaches applied to a decision problem formulated as a continuous or mixed (i.e. both continuous and discrete) one. This separation is performed according to the way the different available alternatives (actions or strategies) are considered.

Discrete decision problem approaches

In this case, approaches are met where a possibly large but in any case discrete and definite set of potential actions or strategies – in the sense described in 'Alternative Options and Strategies' – is considered. The final assessment and selection under this category may be based on various sub-approaches as depicted in Figure 5.5. These are as follows.

Simulation based approaches

The simulation-based approaches can be either simplified (analytical methods) or detailed (numerical methods) using powerful simulation programmes (Clarke, 2001). Indicatively, the simplified methods are the degree-day method, the variable-base degree-day method, the bin method and the modified bin method (Homoud, 2001; Kreider et al, 2002).

In the simulation-based process, a basic model is developed using simulation tools. Then, through an iterative procedure, a series of recommendations are defined, using the simulation energy analysis in order to 'move' the building from a typical construction to a best practice construction (Horsley et al, 2003). These recommendations may include increase of insulation, use of innovative highly efficient glazing, change of building shape and aspect ratios, etc. (Table 5.1).

The detailed simulation programmes are analysed by many authors (see for example, Hong et al, 2000; Homoud, 2001). An overview of the computational support for energy efficient building components is provided by Wilde and van der Voorden (2004). The main simulation tools for energy analysis are TRNSYS, DOE-2, EnergyPlus, BLAST, ESP-r, etc.

TRNSYS is used by a number of researchers. Florides et al (2002) used TRNSYS to examine measures such as natural and controlled ventilation, solar shading, various types of glazing, orientation, shape of buildings, and thermal mass aiming to reduce the thermal load, while Zurigat et al (2003) used TRNSYS to evaluate different passive measures aiming to reduce the peak cooling load of school buildings.

EnergyPlus is used by Becker et al (2007) to assess specific factors of building design elements (window orientation, glazing type, thermal resistance of walls, etc.) and 20 ventilation strategies for schools' energy consumption and efficiency.

Visual DOE is used by Tavares and Martins (2007) to perform a sensitivity analysis that results in energy efficient design solutions for a specific case study. A significant number of predefined solutions are modelled and evaluated.

By concluding the simulation-based approach, the most appropriate energy tool is selected based upon:

- type of criteria to be assessed;
- the required accuracy;
- easiness;
- availability of required data;
- building's phase (design or operational).

Multi-criteria decision analysis approaches

Multi-criteria decision analysis (MCDA) is used by many researchers to support the synthesis of the potential actions and includes areas such as multi-attribute utility theory (Keeney and Raiffa, 1993) and outranking methods (ELECTRE method, see Roy, 1991). Moreover, MCDA supports the inclusion of subjective aspects through the decision makers' preferences that influence the decision process.

In the building design process, MCDA is utilized by:

- Gero et al (1983) to assess the optimum orientation, window fraction, etc. versus capital cost, area that is used and total thermal load ration; and
- Jedrzejuk and Marks (2002) to find the optimum solution for building shape, internal partitions and optimization of heat sources for blocks of flats, using an iterative procedure.

In the operational and retrofit stage, MCDA is introduced by various researchers. Combinatorial and outranking methods are used by Blondeau et al (2002) to assess indoor air quality, thermal comfort and energy consumption. With the combinatorial method, each potential action is assessed via a utility function that fits the decision process. Then each action is ranked according to its utility function. In the outranking method, the potential actions are compared in pairs and final ranking of the predefined actions is extracted after ascending and descending ranking. The utility functions used for each action are I_{area}, which is the surface area of the triangle shaped when joining the coordinates of each considered action in the three-dimensional criteria space (Figure 5.6) and I_{norm}, which corresponds to the norm of the vector joining the origin to the action point.

A similar approach is followed by Rutman et al (2005) who use the multi-criteria ELECTRE method to evaluate the thermal comfort, acoustic comfort and indoor air

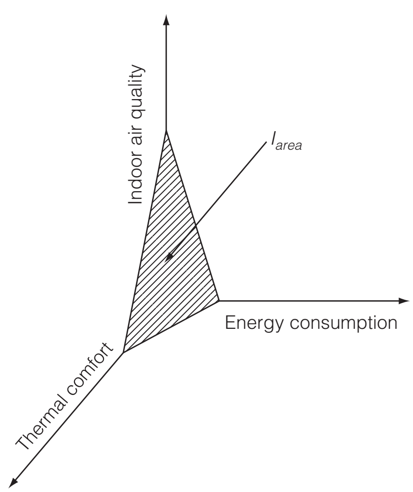

FIGURE 5.6 The utility function to assess the indoor thermal comfort, air quality and energy consumption (Blondeau et al, 2002)

distribution in an office air-conditioned room. The purpose of the procedure is to extract design rules for air-conditioning systems that satisfy indoor comfort requirements.

Outranking methods with criterion by criterion comparison are also used by Rey (2004). ELECTRE III method is used to rank the three strategies discussed in 'Alternative Options and Strategies' after ascending and descending ranking. Each criterion is weighted according to its importance. The retrofitting strategies are placed in a final ranking if they have the same position in the ascending and descending ranking.

Moreover, the Office Rating Methodology (ORME) proposed by Roulet et al (2002) uses ELECTRE algorithms to rank office buildings based on comfort, waste and energy consumption criteria. The ORME method introduces the energy efficient retrofit score (EERS) which is defined as:

$$EERS = 1 - \frac{\text{Distance of scenario i from the target}}{\text{Distance of base case from the target}} \quad [5.1]$$

Different predefined scenarios are evaluated using the EERS.

Another simplified MCDA approach considering the economic benefits resulting from energy efficiency investments is the two-factor method proposed by Martinaitis et al (2007). This method, which uses only two criteria in order to overcome the problem of using complex MCDA techniques, is applied to building retrofits or renovations. The investments are differentiated between those relating to energy efficiency and those relating to building renovation. The costs and benefits of measures incorporating energy efficiency and building renovation are then separated by using the building rehabilitation coefficient (Martinaitis et al, 2004). The cost of conserved energy index is used to evaluate the energy efficiency investments. Homogeneous building renovation measures are evaluated using standard tools for the assessment of investments in maintenance, repair and rehabilitation.

Kaklauskas et al (2005) used multivariant design and MCDA for the refurbishment of a building envelope to prioritize and rank the alternative solutions. The alternatives' significance, utility degree and priority are extracted using this methodology and, as a consequence, the strongest and weakest points of the refurbishment are revealed.

Pasanisi and Ojalvo (2008) developed an MCDA tool called REFLEX (Effective Retrofitting of an Existing Building Tool) for building refurbishments. The multi-criteria approach ranks the retained solutions according to the end users' point of view and energy suppliers' satisfaction.

Other tools that are used in the literature for energy efficiency and indoor environment using multi-criteria decision aid are the EPIQR (Energy Performance Indoor Environmental Quality Retrofit Method for Apartment Building Refurbishment) for residential buildings (Jaggs and Palmer, 2000; Flourentzou and Roulet, 2002) and the TOBUS (Tool for Selecting Office Building Upgrading Solutions) for office buildings (Caccavelli and Gugerli, 2002).

Combined approaches

Combinatorial multi-criteria decision aid in a knapsack model is proposed by Alanne (2004) to support building retrofit and renovation. The knapsack problem is a well-known problem in combinatorial optimization. It derives its name from the maximization problem of the best choice of essentials that can fit into one bag to be carried on a trip. In the approach, proposed by Alanne, MCDA is used to extract the utilities of the renovation actions proposed, as well as the total utility versus the selected criteria. The obtained utility scores are then used as weights in a knapsack optimization model to identify which actions should be undertaken, through the maximization of the following objective function, subject to budget constraints (Alanne, 2004):

$$ObjF = max \sum_{i=1}^{n} a_i S_i \qquad [5.2]$$

where a_i is a binary decision variable corresponding to the renovation action i ($a_i = 1$ if action i is carried out, else $a_i = 0$) and S_i is the utility score of the renovation action i. This model is suitable for use when the number of renovation actions is large and their combinations lead to a great number of options that cannot be assessed manually.

Multi-objective programming (MOP) approaches

Multi-objective decision aid deals with mathematical models including more than one objective function (Mavrotas et al, 2008). As a consequence of vector optimization, multi-objective problems do not provide a single optimal solution. The main reason is that an 'ideal' solution optimizing all the objective functions, simultaneously, is seldom feasible. Multi-objective optimization algorithms are used by various researchers to find the Pareto optimal solutions that correspond to the Pareto frontier (Figure 5.7), which is used to facilitate the determination and understanding of the trade-off relationships between the optimization objectives (Kalyanmoy, 2001). The scope of applying multi-objective optimization is twofold: first to find solutions as close as possible to the true Pareto optimal frontier and, second, to find solutions as diverse as possible in the Pareto frontier (Fonseca and Flemming, 1998).

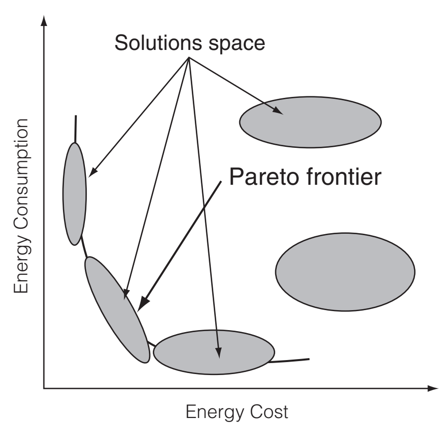

FIGURE 5.7 The Pareto frontier for two criteria

Although MOP approaches can be utilized for the specific problem and under the conditions described in the beginning of this section, the authors did not find any MOP discrete approach in the literature.

Continuous or mixed decision problem approaches

In the discrete decision problem approaches, the whole process, as well as the final decisions, are significantly affected by the experience and the knowledge of the corresponding building expert or the decision maker. Although this experience and knowledge are certainly significant and irreplaceable elements in the whole process, it is necessary to develop practical tools that will assist him/her in taking into account as many feasible alternatives and decision criteria as possible, without the restrictions imposed by predefined actions or strategies. To overcome this shortcoming of the discrete decision problem approaches, the continuous or mixed decision problem approaches have emerged. These latter approaches are mainly based upon the concepts of MOP techniques, a scientific area that offers a wide variety of methods with great potential for the solution of complicated decision problems. The main characteristic of this approach is that the whole possible set of feasible measures is taken into account. Some examples of continuous or mixed decision problem approaches are given below:

- The thermal design of a building is optimized using the Nelder-Mead (downhill simplex) method (Nelder and Mead, 1965) and the non-random complex method (Mitchell and Kaplan, 1968) by Bouchlaghem (2000). The Nelder-Mead method minimizes an objective function in a multidimensional space. The non-random complex method is similar to the downhill simplex method, except that, when the decision variables fall outside the constraints or boundaries, they are replaced by the boundaries. The decision support procedure follows three steps: (a) specification of the building, (b) simulation and (c) optimization, with a continuous interaction between the simulation and optimization steps in order to extract the optimum values of the decision variables that satisfy the comfort criterion. The methodology provides the optimum elevations and angles of the building that minimize discomfort.
- More recently, building envelope improvement during either the design or operational phase using MOP has been proposed by Diakaki et al (2008). The developed decision problem is a mixed-integer multi-objective combinatorial optimization problem with two competitive criteria (cost and energy efficiency). The problem is solved using three different MOP techniques: the compromise programming; the global criterion method; and the goal programming. This approach is still at an early stage of development.

The complexity of the decision problem resulting from the consideration of multiple criteria and its formulation as a continuous or mixed decision problem has led various researchers to use genetic algorithms (GAs), usually coupled with simulation tools. The notable characteristic of GAs compared with other optimization approaches is that they facilitate the exploration of the decision space in the search for optimal or near optimal solutions. Applications of multi-objective genetic algorithms in buildings include the following:

- Wright et al (2002) use GAs to find the optimum Pareto set of solutions to trade-off between the HVAC system energy cost and occupant discomfort. The solutions evaluation is performed using a simplified model.
- Wang et al (2005) use GAs for building design. The two objectives that are minimized are the life cycle cost and the life cycle environmental impact. GAs generate simultaneously a group of solutions and search the state space based on the evolution principle of mutation and crossover (Michalewicz, 1994).The Pareto frontier extracted by the specific optimization procedure provides the best solution for each criterion, the target for each criterion at the design stage and the trade-off relationship between the life cycle cost and life cycle environmental impact.
- Verbeeck and Hens (2007) proposed one more multi-objective GA approach. The design alternatives of the buildings are merged in a chromosome. The fitness function represents the three objectives, i.e. primary energy consumption, net present value and global warming potential. During the assessment process, each solution is ranked according to its fitness for the three objectives. The assessment process is supported also by simulation using TRNSYS. The ranking is based on the Pareto score of the solution, being the number of solutions in the population by which the solution is dominated. The Pareto concept combined with GAs does not result in one single optimum but in the trade-off between the objectives.

ONLINE APPROACHES

In the operational phase of a building, energy efficiency is achieved by data collection and BEMS, thus improving the building's intelligence. The architecture of a BEMS incorporating energy efficiency techniques is illustrated in Figure 5.8.

BEMS can contribute to a significant reduction of the energy consumption of buildings and improvement of the indoor comfort through advanced control techniques (Kolokotsa et al, 2005). Modern control systems provide an optimized operation of the energy systems while satisfying indoor comfort. A comparison of the various control schemes for buildings (Proportional–Integral–Derivative, On–Off, fuzzy, etc.) is provided by Kolokotsa (2003). Recent technological developments based on artificial intelligence techniques (neural networks, fuzzy logic, GAs, etc.) offer several advantages compared with classical control systems. A review of the fuzzy logic contribution in indoor comfort regulation as well as HVAC control and energy efficiency is performed by Kolokotsa (2007). The role of neural networks in buildings is analysed by Kalogirou (2006). A model-based supervisory control strategy for online control and operation of a building is presented by Ma et al (2008).

Control rules concerning the energy efficiency via BEMS can be (Mathews et al, 2000; Doukas et al, 2007):

- Start/stop optimization: Rules about model starting and ending, according to each area or room working hours, including pre-warming and smooth power-down procedures for accomplishing the possible energy savings.
- Setpoint-related energy management strategies: Rules to reduce the energy consumption by regulation setpoints (temperature reset, zero energy band control, enthalpy economizer, adaptive comfort control).

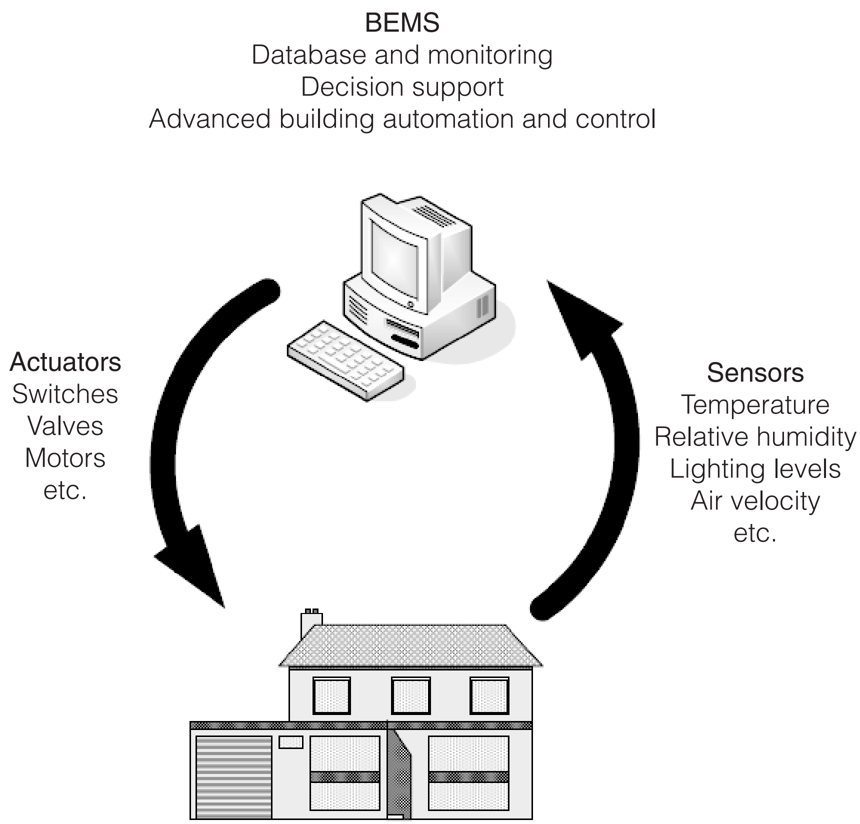

FIGURE 5.8 The building energy management system and its role in energy efficiency

- Procedural hierarchy: Rules concerning the intervention hierarchy for the temperature, relative humidity, air quality and luminance adjustment for their optimum operation.
- Energy management optimization: Rules that allocate high-consumption periods in order to propose actions for peak shaving and shifting (demand limiting, duty cycling, load resetting, etc.).

Using BEMS, the required data that in the design phase are extracted by simulation, are taken by the BEMS database. Usually, the energy efficiency measures proposed are pinpointed by a specific list of actions based on energy experts' experience and the criteria assessed can differ according to the application's scope (Doukas et al, 2008).

BEMS and intelligent buildings can also be combined with advanced decision support methodologies to monitor and improve building performance during real-time operation. In terms of online advanced decision support, the following approaches have been found in the literature:

- Analytic hierarchy process (AHP) survey is proposed by Wong and Li (2008) to weight the most critical selection criteria for intelligent buildings. In their survey, the work efficiency criterion (e.g. system's reliability, compliance, etc.) of a BEMS is the most critical one, followed by indoor comfort, safety and cost-effectiveness.
- Analytic network process (ANP), an MCDA approach, is implemented by Chen et al (2006) for lifespan energy efficiency assessment of intelligent buildings. The MCDA is implemented in four steps: model construction; paired comparisons between each two clusters or nodes; supermatrix calculation based on results from paired comparisons; and finally result analysis for the assessment (Figure 5.9). Two alternatives are assessed. The alternative with the highest rate is the one that regulates the building performance of lifespan energy efficiency with the best solutions for building services systems, least energy consumption, lowest ratio of wastage, and lower adverse environmental impacts.
- Gradient-based multi-objective decision support algorithm is proposed by Atthajariyakul and Leephakpreeda (2004) for the real-time optimization of the HVAC system with criteria the thermal comfort, the CO_2 concentration and the energy consumption. The criteria are weighted and summed to formulate the objective function of the optimization and decision support procedure. The weights are set by

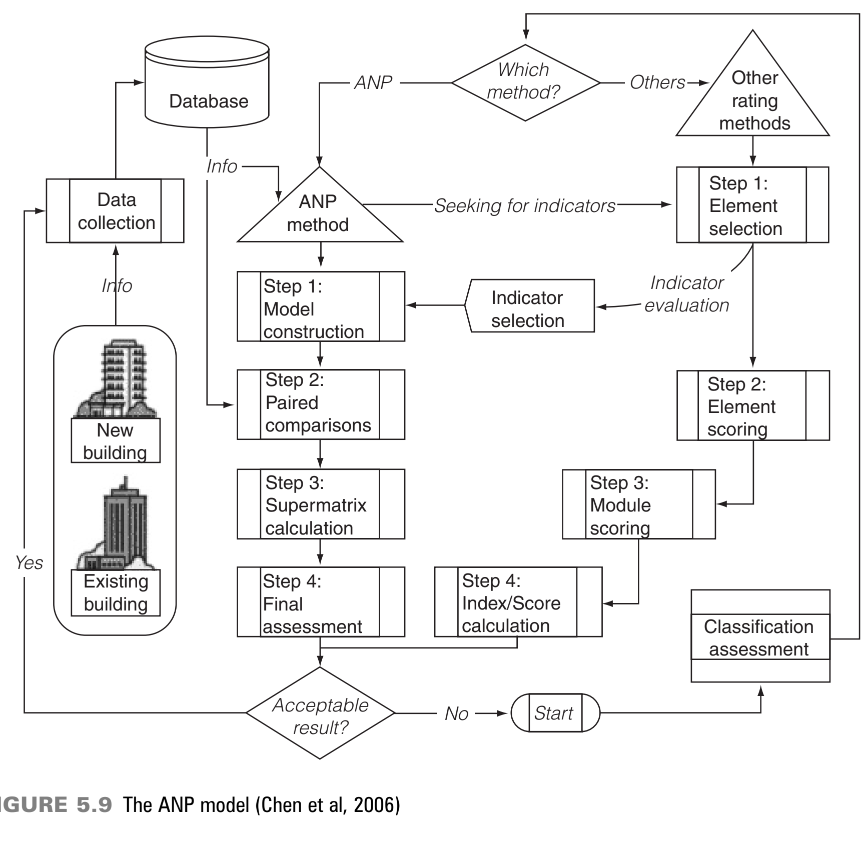

FIGURE 5.9 The ANP model (Chen et al, 2006)

the decision maker. The authors achieved optimum setpoints for the HVAC system by simultaneously maximizing the thermal comfort and the indoor air quality and the energy consumption.

DISCUSSION

Decision problems about a building's sustainability are usually unstructured and ill defined. Moreover, they are characterized by competitive objectives, they involve multiple stakeholders and key actors, dynamic and uncertain procedures and limited timeframes to make significant decisions. Another important issue is the fact that with technological developments in the field, the solutions and decision alternatives are steadily increasing.

The decision makers in the domain are the end users, the design team, the maintenance and operational team, organizational teams, etc. that usually have conflicting subjective preferences and fragmented expertise. Therefore, the role of decision support is critical. Although, as stated in the literature, decision support systems (DSS) should be used to aid decision makers in their work, in practice, DSS can be used to restrict or expand the decision maker's options and to facilitate or provide redirected options. Provision of only a limited set of operations or criteria leads to restrict the techniques and solutions that can be applied and consequently restricts the decision-making process. On the other hand, the inclusion of many objectives and the permitting of user specification of input data, system parameters and models, generally increases system flexibility and increases decision support freedom.

Based on the overall analysis of the present chapter and since the energy efficiency and environmental performance measures can be of a discrete or a continuous nature, the decision variables and consequently the corresponding decision problem can be either discrete, continuous or mixed. For this reason, the approaches employed to analyse and solve this problem can be:

- MCDA approaches where an optimum solution is selected or ranking is performed for a finite set of alternatives based on a set of criteria. This methodology is mainly used for discrete problems, but it can be used for continuous problems as well, if the decision variables are discretized. The advantage of the MCDA approaches is that the decision maker can easily understand the problem and express his/her preferences, while their main drawback is usually the large number of alternative options to be considered. In many cases, researchers perform a preliminary screening phase to eliminate those with a limited or negligible contribution to the criteria (Blondeau et al, 2002; Becker et al, 2007).
- MOP approaches, which target the optimization of a set of objective functions subject to a set of linear or non-linear constraints. Although these approaches are mainly utilized for continuous decision problems, they can also be used for discrete problems. In MOP approaches, the problem is formulated as an integer or a mixed integer mathematical programme. The advantage of such a treatment is that the decision problem is structured in a holistic way. Moreover, the number of alternatives, i.e. the decision space that can be studied, is not limited as it is not necessary to enumerate the set of actions to be considered. The main drawbacks of

the MOP approaches are on the one hand the difficulty in modelling the objective functions and constraints with mathematical equations and on the other hand the complexity and the problem size.

- The third approach is a combination of the above two approaches in two ways:
  - Initially MOP is performed to evaluate the Pareto front and afterwards MCDA is used for the selection of the optimum solution(s).
  - Initially MCDA is utilized in order to evaluate the alternatives on specific criteria and estimate an aggregated 'score', which is then introduced in a mathematical programming problem with a single objective function for the evaluation of the optimum solution.

A critical issue that the above analysis revealed is the role of simulation in the building's sustainability. The approaches used for energy efficiency and minimization of the environmental burden in the building sector are in most cases based on simulation analysis. Even when advanced decision support (i.e. MCDA, MOP) is introduced, the evaluation and the assessment of the decision support process are performed via dynamic or simplified models. Usually, a first evaluation of the alternative options is initially performed through, for example, simulation and then an MCDA technique is employed to aggregate the simulation results and provide a trade-off between the alternative options that is expected to enable the researcher to reach a better decision. In past decades, many efforts were dedicated to developing simulation tools in order to model the dynamics of energy and the indoor environment. Although valuable for detailed design and analysis, few methods are able to simultaneously handle the thermal, visual and indoor air quality aspects in conjunction with energy demands and environmental burden prediction. Therefore, the decision support, if multiple criteria are set, should come from different simulation models that sometimes are not compatible with each other. New simplified tools that integrate several aspects of the building sustainability sector are needed in order to facilitate the decision support applicability.

An additional critical point in the analysis of the present chapter is the fact that in the building sector predefined actions and decision variables are evaluated against a set of decision criteria. This procedure is met in both the design decision phase and in the operational decision phase. Since the predefined actions and options are selected by building experts, the selection procedure is influenced by their relevant expertise. Consequently, to some extent the decisions are biased by the building experts' knowledge and subjective preferences. The end user's criterion is viewed only as the economic aspect of the overall procedure. The economic aspect though, in most cases, is the overriding criterion. Conventional economic indices such as net present value and internal rate of return are not explicitly representative for buildings' sustainability. The cost of conserved energy introduced by Martinaitis et al (2004) provides an alternative view of buildings' related costs by separating investments into those that are absolutely necessary for building renovation and those that contribute to energy efficiency.

CONCLUSION AND FUTURE PROSPECTS

Energy efficiency, the indoor environment and reduction of buildings' environmental impact are the major priorities of the energy and environmental policy worldwide.

In the decision support process, several measures are available, and the decision maker has to take into consideration environmental, energy, financial and social aspects in order to make an optimum design or operational choice. The problem of the decision maker is characterized by the existence of multiple and in several cases conflicting objectives each of which should be optimized against a set of realistic and available alternatives that is influenced by a set of parameters and constraints that should be taken into account.

Consequently, the decision maker is facing a multi-objective optimization problem that up to now is usually dealt with by using either simulation or multi-criteria decision-making techniques that concentrate on particular aspects of the problem.

Thus, there is a need for further development of the decision aid systems to support building experts in the application of their expertise, and assist less-experienced decision makers to approach decisions in the same way as experts would, while taking into account the continuous development of technological expertise in energy efficient solutions.

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