Maintenance, Retrofit and Operation Decision Support Tool for Both Domestic and Non-domestic Buildings

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ABSTRACT

There is great potential for novel decision support tools to aid in the provision of tailored advice for both domestic and non-domestic buildings. The method described in this paper will rely on a combination of data from BIM, monitoring technologies such as smart sensors and performance-based analysis, user behaviour, and expert knowledge, for the development of a decision support tool for maintenance, retrofit and operation. It will present the concepts and research work behind the development of a novel tool to automatically generate maintenance and retrofit advice at different levels of abstraction taking into consideration the requirements of different stakeholders, building performance analysis (BPA), standards guidelines and regulations. Design4Energy (D4E) EU project engaged into the development of an optimised design methodology, which uses decisions making tool based on expertise from a combination of different subject fields feed into a statistical model. Analytic Hierarchy Process (AHP) is adopted for the development of the tool as it uses priority theory which decomposes any complex multi-dimensional decision making problem into a system of hierarchies. This looks into the historic type of experiences while predicting the future building performance and takes into account the operation scenarios and maintenance activities. It logically incorporates data and expert's judgement in the model to identify criteria to enables decision making.

INTRODUCTION

EE is paramount in ensuring the energy security and sustainability of Europe, and Information and Communication Technology (ICT) has a fundamental role to play in delivering that energy efficiency (EE) (Barroso, 2011; EU commission, 2009). Among those technologies are smart metering and control in domestic and non-domestic building, smart grid for energy distribution and dispersed renewable generation, demand response / demand management and energy balancing within the neighbourhood. The energy consumed by buildings to maintain their operations (including heating and cooling plus power for lightning, appliances and building services operations) contributes to a large portion of greenhouse gas generation (Schlueter, 2009). A number of building regulations such as the Leadership in Energy and Environmental Design (LEED, 2007) in the USA, EPBD in EU (Casals, 2006), have emerged with the aim to reduce the amount of CO2 produced by buildings. This paper presents the D4E project plans for EU buildings EE through a novel ICT based decision support tool for tailored maintenance, retrofit and operation measures. Current trends in decision support for improved energy performance as reported by many researchers consist of new approaches to determining the retrofit effectiveness of houses based both on expected energy savings and the increase in market value of renovated buildings (Zavadskas et al., 2008). They consider, retrofit scenarios for buildings developed under a set of determinant, i.e. retrofit investment packages and making judgemental decisions in collaboration with the relevant stakeholders which is a rather experience based manner. Energy consultants, architects, etc. play here a crucial role and guide through the retrofitting process. They most likely will use EPBD compatible software to analyse the initial state of the building (data entry, etc.) to get some numbers on the energy demand versus costs of the different options. However, the EPBD software will not recommend solutions but will only give the user the possibility to run/compare different options (performs the calculation). Other none energetic aspects will basically only be covered by the background and experience of the energy consultant/architect. D4E project deals with optimised design for EE buildings that are integrated in the neighbourhood energy systems. Covering all building life cycle stages in the development of this innovative methodology will allow stakeholders to predict the current and future EE of buildings. It is agreed that to create long term EE building we must not only consider the present building life cycle scenarios but also accurately predict the future (Gluch, 2004).

The proposed methodology will use energy attributes of building components, deterioration of the building components and systems, neighbourhood energy systems, energy related parameters, energy simulation tools and current usage parameters of the occupants, derived from maintenance and operation data. This technology will allow stakeholders to explore various design options and make validated and qualified choices as early as possible. To possibly consider building performance in the early design stages, access to all information defining a building such as its form, materialization and technical systems is necessary. BIM is a digital representation of physical and functional characteristics of a facility. Individual behaviour was also explored (Wilson, 2007) in the development of different models of decision making. Four perspectives were reviewed: conventional and behavioural economics, technology adoption theory and attitude-based decision making, social and environmental psychology, and sociology. Some individual decision models are founded on informed rationality or psychological variables, and others emphasize physical or contextual factors from individual to social scales. The lessons learned are drawn from both intuitive and reasoning-based types of decision as well as from a range of decision contexts that include capital investments in weatherization and repetitive behaviours such as appliance use.

In the concept design description the integration of existing solutions and data bases will be included. BMS (Building Management Systems) will be enabled to understand the “context” in which a building is operated. This context is specified by user preferences, energy tariffs, and energy services offered, maintenance offers & requests. The technical specification for interaction of energy using devices and benchmarking for the decision support tool development will be conducted to specify properties of the building in dynamic mode with high level of accuracy including coordination between energy using devices within building and designs in terms of communication protocols and type of data exchanged. This will involve design requirements and guidelines for each component of the system.

DATA FOR DECISION MAKING PROCESS

Besides regulation and stakeholders requirements data, the components and energy systems data bases which include static information component (e.g. building, geometry, mechanical equipment schedules etc.), were used to store (1) static information in the Industry Foundation Classes (IFC) compliant files and required by other modules; (2) benchmarking operational information component, used to store operational information from others similar real cases; (3) simulation information component, used to store simulation outputs from simulation module; (4) fault detection and diagnostics (FDD) information component, used to store FDD inputs from similar real cases; (5) maintenance and operational data. In D4E data analytics based on building energy performance modelling of the results obtained from the stored databases and form historic data from monitoring sensors (in the case of new build could be taken from similar existing buildings) with relation to the standards benchmarks will be undertaken to assess energy consumption. Furthermore, building user’s behaviour will be simulated based on energy related actions and individual preferences which will complement the set of data, for which appropriate feedback methodology will be based on decision support as shown in figure 1.

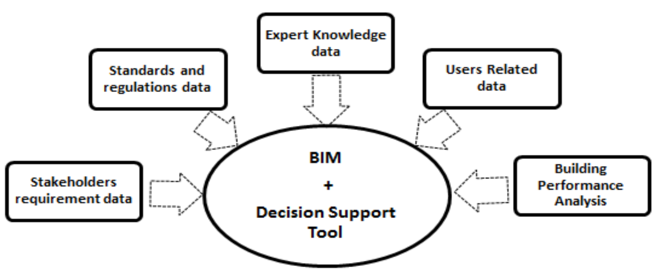

Figure 1. Multidisciplinary information and expertise to support decision making.

REGULATIONS BASED CRITERIA

The standard methods and benchmarks for consideration in this work include CIBSE (Chartered Institute for Building Services Engineers) TM22, TM46, TM39, TM46, TM 47 and the AM11 Building Energy and Environmental Modelling (BEEM). Within Europe the Energy Performance of Buildings Directive (EPBD) takes into account outdoor climatic and local conditions as well as indoor climate requirements and cost-effectiveness. The BREEAM (Lee, 2008) process mitigates the negative impacts of new buildings on the environment allows cost effective, independent and scientifically authoritative manner.

BUILDING PERFORMANCE ANALYSIS DATA

As the most effective and important design decision occur in the early design stages where it is crucial to accurately account for EE and reduced CO2 emissions solutions as part of the design. The poor integration of building components at the design stage in the conventional ways leads to costly and unsatisfactory modifications afterwards to meet the performance criteria (Schlueter, 2009). Within the ICT for EE paradigm, Computer Aided Architectural Design (CAAD) tools have led to impressive results in terms of integrating sustainability solution with architectural aspects. The HESMOS (Liebich, 2011) considered that architects and facility managers should be enabled to undertake thermal simulation and accurate estimation of the building life cycle energy costs into a BIM platform. These simulation tools are specifically designed for those with expert knowledge to correctly choose and input the data sets into the software, run the simulations and analyse the generated results. BIM is a rich repository of multidisciplinary data. These types of information include geometric (3D models), semantic (specification and properties of components such as U-value) and topological information in terms of dependencies of components. IFC is a non-proprietary BIM developed by the International Alliance for Interoperability (Bazjanec, 2004).

a. Physical models BPA. This involves first an understanding of the conversion of any Physical Model into an Analytical Model for BPA, and then an understanding of how that process impacts the structure of the Physical Model. Physical calculation models perform calculation of detailed tasks as well as overall energy consumption of a building. These include zone loads, day-lighting and solar to multi-zone air flow, where highly precise calculations for every possible engineering activity are available. One good example here is Revit Physical Model set up to carry out Building Performance Analysis using the IES <VE> Direct Link found in Revit MEP or gbXML exports from Revit Architecture (Azhar, 2001). Many expert tools use physical calculation models for the calculation such as TRNSYS, IES Virtual Environment or EnergyPlus. Necessary information input to run expert simulations is extensive, so is knowledge to perform and interpret the simulation results. As one of the few tools with focus on a more graphical interface and less effort to conduct a performance analysis, Ecotect is targeted at the architectural design process. Importing and exporting of building geometry to define the simulation model is error-prone and tedious, especially as geometry models established in CAD software are often not suitable as simulation models. The simulation results and possible conclusions remain in the simulation software; a feedback into the design software is not possible as yet. Changes in design due to performance criteria have to be done manually in the design software, the model has to be exported and simulated again. These steps have to be repeated after every change in design. As long as a fully functional IFC-based data exchange is not yet available, external tools utilizing a physical calculation model for performance assessment only apply for critical design tasks (Hassanain, 2001).

b. Statistic models BPA. Statistic calculation models estimate the total energy demand, heating or lighting energy demand. Regulations refer to statistical calculation models for mandatory application in the building process. The EU Directive on Energy Performance of Buildings states the general framework for the calculation of energy performance and building categories to be included. The focus is on relatively simple “hand-calculation” methods, and not building simulation computer models, which are much more difficult to validate and standardise. The standard prEN ISO 13790 which covers thermal performance of buildings, calculation of energy use for space heating, provides a good starting point. Preferably, as few calculation models as possible should be used to cover the different building categories. It may, however, be necessary with more than one model, depending on the desired output and accuracy. Instead of calculating the physical processes within the building, empirically found factors are applied, delivering rough estimates that are necessary to satisfy the regulations. Typical statistic calculation tools are spreadsheet-based or even web based applications such as IdeaXP (Zweifel, 2005).

DECISION MAKING METHODOLOGY

The different sets of data described so far will serve to dictate the key decision for design, retrofit, maintenance or operation of the building. In management science, Operations Research (OR) deals with the application of advanced analytical methods to help make the best possible decisions. A branch of OR which is of interest to us is the Multiple Criteria Decision Making (MCDM), which is a procedure to integrate multiple indicators into a single meaningful index to allow ranking and comparing for decision making. MCDM is an efficient statistical method to combine component indices arising from all the information sources into a single overall meaningful index, therefore ranking and comparing are feasible. MCDM has potential for analysing complex real problems due to its ability to weight different alternatives (requirement, choice, strategy, policy, scenario can be used synonymously) and make judgement on various criteria for possible selection of the best/suitable alternative(s) which further can be explored in-more-details for their possible implementation. A typical MCDM problem is when there are a number of criteria to assess a list of alternatives. Each alternative is therefore represented by a single value for each of the criteria to permit the assessment and/or ranking, see figure 2. Complex decision problems require the consideration of multiple criteria (Zeleny, 1982).

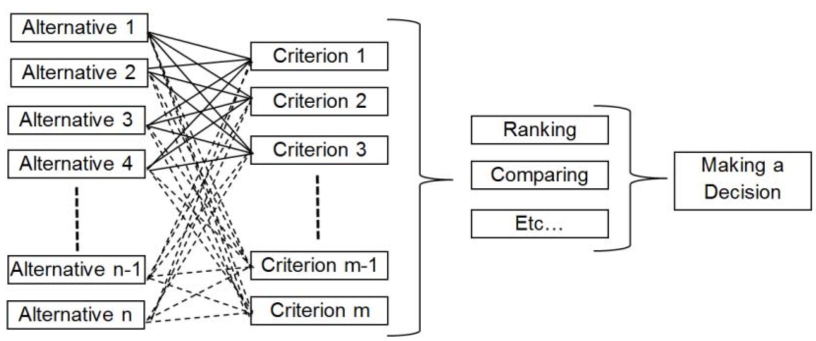

Figure 2. Multi criteria decision making (MCDM) process to be adopted in D4E

The weighted sum model (WSM) is the simplest of MCDM, which is applicable only when all the data are expressed in exactly the same unit otherwise the final result, is ironic While weighted product model (WPM) is a modification of the WSM, which overcomes some of the WSM weakness. The analytic hierarchy process (AHP), as proposed by Saaty (1994) is a later development and it has recently become popular. Some other widely used methods are the ELECTRE and the TOPSIS methods. Filar (2009) described in detail the TOPSIS method and used entropy as a basis to determine the importance of weights and applied the MCDM technique to assess the possibilities available. An MCDM process include: (i) determining the relevant criteria and alternatives; (ii) attach numerical measures to the relative importance of the criteria and the impact of the alternatives on these criteria and (iii) process the numerical values to determine a ranking of each alternative. WPM uses multiplication in the model instead of addition in WSM. Each of the *m* alternatives is compared with the others by multiplying a number of ratios, one for each of the *n* criterion. Each ration is raised to the power equivalent to the relative weight of the corresponding criterion w_j. Therefore, to compare two alternatives A_K and A_L, this ration equation is used:

$$R\left({A_K}/{A_L}\right) = \prod_{j=1}^{n}\left({a_{Kj}}/{a_{Ij}}\right)^{w_j} \quad for\ K = L = 1,2,3,\dots m \qquad \text{(Equation 1)}$$

Where *a*, is the actual value of the *i-th* alternative in terms of the *j-th* criterion. If the term $R(A_K/A_L)$ is greater than or equal to one, then A_K is more desirable than alternative A_L. The best alternative is the one that is better than or at least equal to all other alternatives.

However, the Analytic Hierarchy Process (AHP) method that is based on priority theory decomposes a complex multi-dimensional decision making problem into a system of hierarchies. AHP is a structured technique for organizing and analysing any complex situation for possible decision using statistics and psychology, which is used in fields such as government, business, industry, healthcare, and education. The product of AHP is an *m***n* matrix (*m* alternatives * *n* criteria). It uses the relative importance of the alternatives in terms of each criterion. The AHP adds valuable capability to the MCDM as it has the ability to logically incorporate data and expert's judgement in the model for measurement and prioritising intangibles to deal with interdependence allowing corrective measures. As a complex and unstructured situation is broken down, its components are arranged into a hierarchic order including criteria and alternatives. Numerical values (from 1 to 9) are assigned to subjective importance of each criterion toward an overall prioritisation of criteria and alternatives. To calculate the priorities/weights of these indicators eigenvector method is used for pairwise comparison matrix. *N (N-1)/2* pairs of these indicators are to be assessed/ evaluated. AHP derives ratio scales from paired comparisons in four steps which are: (i) developing a hierarchy of factors impacting the final decision, where the last level of the hierarchy is the three candidates as an alternative, (ii) pair-wise comparisons between the factors using inputs data (expert and/or user judgement); (iii) evaluation of relative importance weights at each level of the hierarchy; (iv) combining relative importance weights to obtain an overall ranking of the three candidates.

The core of MCDM methods consists of the construction of pairwise comparison matrices and the extraction of weights by means of the principal right eigenvector. A Weight of a criterion indicates the priority assigned to the item by the decision maker while ranking the alternatives. Methods for computing the weights include Rating Method and Entropy Method. The rating method requires the decision maker to express all the criterion weights on a numerical scale. Linguistic variables in a fuzzy environment in the form of Triangular Fuzzy Numbers (TFNs) are also used to determine the weights of criterion. While Entropy method measures the uncertainty associated with random phenomena of the expected information content of a certain message and this uncertainty is represented by a discrete probability distribution. The Entropy Method estimates the weights of the various criteria from a matrix independently of the views of the decision maker. If the entropy value is high, the uncertainty contained in the criterion vector is high, diversification of the information is low and correspondingly the criterion is less important. The Bradley–Terry–Luce model (Tutz, 1986) is often applied to pairwise comparison data to scale preferences. A probability that object j, is judged to have more of an attribute than object i, is: $Pr\{X_{ji} = 1\} = \frac{e^{\delta_j - \delta_i}}{1+e^{\delta_j - \delta_i}} = logit^{-1}(\delta_j - \delta_i)$; (Equation 2)
where, δ_i, is the scale location of object i, $logit^{-1}$is the inverse logit function.

CONCLUSIONS

In an attempt to quantitatively help making decision for EE in building design stage, this work considered both short term performance as well as future scenarios, while also considering all other factors in terms of longevity and deterioration, technology evolution, climate change, user's behaviour, energy neighbourhood configuration, preventive maintenance and renovation. As most of decisions making involve expertise from a combination of different subject fields, we found that AHP which works as a less prescriptive tool opens channels for decision makers to find the best decision which suits their goal within their narrow/expert understanding of the problem and with rational framework for structuring a decision problem. It looks into the historic type of experiences while predicting the future building performance and takes into account the operation scenarios and maintenance activities. MCDM has the ability to logically incorporate data and expert's judgement in the model for prioritising intangibles to deal with interdependence allowing decision making or corrective measures. The components of any complex and unstructured situation will be identified as criteria and the alternatives are arranged into a hierarchic order for prioritisation which is the basis of a decision making.

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REFERENCES

Azhar, Salman, et al. "Building information modelling for sustainable design and LEED® rating analysis." Automation in construction 20.2 (2011): 217-224. To be retrieved at: http://images.autodesk.com/adsk/files/building_ performance_ analysis_using_revit.pdf

Barroso JMD (2011) Growth and economic governance - orientation debate on energy and innovation, Reference: SPEECH/11/1 Date: 05/01/2011, http://europa.eu/rapid/pressReleasesAction.do.

Bazjanec, V. Building energy performance simulation as part of interoperable software environments, Building and Environment 39 (8) (2004).

EU commission 12/3/2009 http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2009:0111:FIN:EN:PDF

Filar, Jerzy A., N. PHILLIP Ross, and Ming-Lu Wu. Environmental assessment based on multiple indicators. Diss. Calcutta Statistical Association, 1999.

Gluch, Pernilla, and Henrikke Baumann. "The life cycle costing (LCC) approach: a conceptual discussion of its usefulness for environmental decision-making." Building and Environment 39.5 (2004): 571-580.

Hassanain, Mohammad A., Thomas M. Froese, and Dana J. Vanier. "Development of a maintenance management model based on IAI standards." Artificial Intelligence in Engineering 15.2 (2001): 177-193.

Lee, W. L., and J. Burnett. "Benchmarking energy use assessment of HK-BEAM, BREEAM and LEED." Building and Environment 43.11 (2008): 1882-1891.

Liebich, T., et al. "HESMOS Deliverable D2. 1: BIM Enhancement Specification,©." HESMOS Consortium, Brussels (2011).

Saaty, Thomas L. Fundamentals of decision making and priority theory: with the analytic hierarchy process. Rws Publications, 1994.

Schlueter, Arno, and Frank, Thesseling. "Building information model based energy/exergy performance assessment in early design stages." Automation in Construction 18.2 (2009): 153-163.

The Leadership in Energy and Environmental Design (LEED) Green Building Rating System, 2007. Available from: http://www.usgbc.org/DisplayPage.aspx?CMSPageID=222.

Tutz, Gerhard. "Bradley-Terry-Luce models with an ordered response." Journal of mathematical psychology 30.3 (1986): 306-316.

Wilson, Charlie, and Hadi Dowlatabadi. "Models of decision making and residential energy use." Annu. Rev. Environ. Resour. 32 (2007): 169-203.

Zavadskas, Edmundas, Saulius Raslanas, and Artūras Kaklauskas. "The selection of effective retrofit scenarios for panel houses in urban neighbourhoods based on expected energy savings and increase in market value: The Vilnius case." Energy and Buildings 40.4 (2008): 573-587.

Zeleny, Milan. Multiple criteria decision making. Ed. James L. Cochrane. Vol. 25. New York: McGraw-Hill, 1982.

Zweifel, Gerhard, et al. "A Design Tool for Wood Fired Storage Appliances." Modelling, Simulation, and Optimization: Fifth IASTED International Conference Proceedings, 2005.