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Assessment of building-integrated green technologies: A review and case study on applications of Multi-Criteria Decision Making (MCDM) method

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ABSTRACT

Retrofitting existing buildings with appropriate green technologies is an important element of strategies to mitigate climate change. The selection of green technologies can be a challenging task, where multiple criteria exist and interrelate. However, it is still common for decisions to be based on a single criterion, such as energy efficiency or cost. This paper aims to evaluate the application of Multi-Criteria Decision Making (MCDM) methods to the selection of green technologies for retrofitting to existing buildings. The paper begins with a review of MCDM methods and the use of these techniques for selecting technologies to retrofit existing buildings. The applicability of Analytical Hierarchy Process (AHP), a widely used MCDM method, is demonstrated through a case study of a building that is part of a university estate. The findings show that AHP can help to formulate the problem, and facilitate the assessment and ranking of retrofitting measures when multiple criteria are jointly considered. We have shown that by considering environmental and economic criteria, control technologies such as variable speed drives in air handling units, rank most highly in this case. It has also been suggested that social criteria, such as occupant satisfaction, should also be considered as part of the sustainability agenda, although this can be more difficult to achieve than consideration of environmental and economic criteria, which are more readily characterised using quantitative data. We conclude by proposing an integrated green technology assessment and selection framework, which is applicable to existing buildings.

1. Introduction

The United Nations Environment Programme (UNEP) has estimated that buildings contribute up to 30% of global annual greenhouse gas (GHG) emissions and consume up to 40% of all primary energy (UNEP-SBCI, 2009). The building sector is recognised as the largest consumer of primary energy, compared to other major sectors such as industry and transportation (Butler, 2008; Pérez-Lombard, Ortiz, & Pout, 2008; Saidur, 2009). Cost effective reductions in GHG emissions and energy savings of more than 30% are possible in many countries (UNEP-SBCI, 2009). As such, the building sector should be a high priority in local, regional, and global climate change mitigation strategies.

Energy efficiency improvement in buildings is one of most effective measures to reduce carbon emissions, especially as many buildings are characterised by poor energy performance (Saidur, 2009; Spyropoulos & Balaras, 2011). Energy efficiency can be reduced significantly through retrofitting existing buildings with new technologies (Ardente, Beccali, Cellura, & Mistretta, 2011; Chidiac, Catania, Morofsky, & Foo, 2011). Given relatively low rates of replacement of existing buildings by new buildings, retrofitting the existing building stock has been identified as having greater potential to improve energy efficiency and reduce GHG emissions than improving standards of new buildings (Energy Efficiency Directive, 2012; Norris & Shiels, 2004; Roberts, 2008).

The performance of existing buildings can be improved using a range of retrofit options, including energy reduction measures and low carbon technologies. Energy reduction measures can include draught proofing measures, improvement in wall insulation and replacement of windows to minimise heat gains. Other measures, such as enhancing natural ventilation and daylight, can further

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reduce energy consumption (Roberts, 2008). A green roof can also be considered as an energy reduction measure suitable for retrofit if it provides insulation and cooling due to evapotranspiration, and can been supported by the existing building structure (Castleton, Stovin, Beck, & Davison, 2010). Low carbon technologies can include solar systems, wind turbines, biomass boilers and combined heat and power systems, which have lower GHG emissions than conventional energy supply systems.

However, the selection of retrofit measures for existing buildings is a complex task. The success of retrofitting is subject to many uncertainties, including occupant behavior, government policy changes and climate volatilities, all of which directly affect the selection and performance of technologies. Other challenges may include financial limitations, long payback periods, and interruptions to operations. At the technical level, different retrofit measures may have different impacts on associated building sub-systems (Ma, Cooper, Daly, & Ledo, 2012). With the rise of sustainability agenda in building sector, it is essential for the decision makers to consider sustainability criteria, which address environmental, economic and social performance. The interdependencies and conflicting nature between these criteria are well recognised. The qualitative and quantitative nature of different criteria also increases the complexity of analysis. Dealing with these uncertainties and system interactions is a considerable technical challenge in any sustainable building retrofit project.

The current decision-making process surrounding building retrofit is commonly based on a single economic criterion, such as a cost-benefit ratio obtained through a financial performance analysis (Nelms, Russell, & Lence, 2005). Faced with lack of established practices in use of decision making tools, designers and building managers are more likely to turn to intuition (Pan, Adrew, Dainty, & Alistair, 2012). Multi Criteria Decision Making (MCDM) methods have been proposed to assist with the selection of green technologies for buildings (Dangana, Pan, & Goohew, 2013). MCDM methods can deconstruct the problem of decision making into discrete steps, compare the relative importance of criteria and select the optimal alternative using rigorous mathematical models. These methods can clarify the interrelations between criteria and minimise the subjectivity of the selection (Linkov & Moberg, 2012). MCDM methods have been used to support design decisions for low carbon buildings (Dawood, Crosbie, Dawood, & Lord, 2013) and in evaluation of climate change mitigation policy instruments (Konidari & Mavrakis, 2007). There is a need to investigate the effectives of MCDM methods to support decisions about technology selection when retrofitting existing buildings.

The aim of this paper is to explore the application of MCDM methods in technology selection for retrofitting existing buildings. Section 2 presents state-of-the-art in green technology selection and reviews the MCDM family of methods. It also provides a discussion on the characteristics of the MCDM methods employed into assessment and selection of alternative green technologies considered for integration into existing building. Section 3 presents a case study. The paper concludes with the merits and limitations of MCDM in the context of building retrofitting, and outlines avenues for future research.

2. Assessment of green technologies for building integration and retrofit

2.1. Decision making with multiple criteria

Robust selection of green technologies takes account of multiple criteria. These criteria can be technical, such as capacity requirements, spatial requirements, reliability and flexibility; economic, such as capital cost, operating cost and maintenance cost; environmental such as carbon reduction and energy saving potential; and social such as occupant health and safety and employment creation. These criteria can influence the decision makers' goal and reflected as different priorities, which may be represented as weightings in decision support systems.

MCDM methods provide mathematical models to weight criteria, score alternatives and synthesize the final results. The process of decision making with several criteria is characterised by following phases (Gore, Murray, & Richardson, 1992):

- objective identification;
- criteria development;
- alternative generation, evaluation and selection;
- implementation and monitoring.

2.1.1. Criteria development and information collection

The principles of good criteria selection are: a systematic approach; consistency; independency; measurability; and comparability (Ye, Ke, & Huang, 2006). The criteria are normally organised in a hierarchy from general to detailed. For each level, criteria should be mutually exclusive but inclusive within the upper level of criteria. However, this rule is not easy to comply with when dealing with sustainability criteria. The economic, environmental, social and technical criteria are interrelated, and if not organised in a clear way, the information can overlap, leading to double-counting in the analysis. For instance, boiler efficiency can be structured under technical criteria, but can also be placed under cost, environmental or social criteria, since boiler efficiency will impact GHG emissions, which influence the environment and human welfare, and will reduce fuel costs. Criteria structuring or specification of the criteria implications at the initial stage can help to define a hierarchy with clear relationships.

The criteria can be collected from a literature review, surveys, interviews and workshops with stakeholders, or the combination of these methods (Pan et al., 2012). A long list of criteria might be collected from expert consultation without much knowledge about interrelationships that could exist among these criteria. However, there are methods available to reduce the number of decision criteria to a representative list. The most common methods are the Delphi, the least mean square (LMS), the minmax deviation and the correlation coefficient method. The Dephi method is based on several rounds of discussions or surveys amongst a group of experts with the aim converging towards a representative set of criteria (Rowe & Wright, 2001). The LMS method is used to eliminate the criteria with similar performance across the alternatives (Guo, 2007). The minmax deviation method is to remove the criteria with less deviation of performance values (Ye et al., 2006). The correlation coefficient method is to analyse the interrelationship between criteria (Papadatos & Xifara, 2013). If the correlation coefficient between two criteria is close to 1, the two criteria are closely related, and therefore one of them can be removed.

2.1.2. Criteria weighting

After establishing the set of criteria, weights must be assigned to reflect on their relative importance. Available weighting methods can be classified into two categories: equal weights method and rank-order weighting method. The equal weights method does not require the decision makers' preferences. The rank-order weighting methods are designed to compare the relative importance of the criteria. These methods include subjective weighting, objective weighting and combination weighting methods. Subjective weighting methods only consider the opinions of decision makers, while objective weighting methods decide the weights based on the criteria value data.

Subjective weighting methods include Simple Multi-Attribute Rating Technique (SMART), swing and pair-wise comparison meth-