Energy and Buildings 72 (2014) 229–237

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Multicriteria evaluation of alternatives for remote monitoring systems of municipal buildings

Aki Pesola[a], Ari Serkkola[a], Risto Lahdelma[b], Pekka Salminen[c,*]

[a] Aalto University, School of Engineering, Department of Civil and Environmental Engineering, P.O. Box 12100, FI-00076 Aalto, Finland
[b] Aalto University, School of Engineering, Department of Energy Technology, Otakaari 4, FI-02150 Espoo, Finland
[c] University of Jyväskylä, School of Business and Economics, P.O. Box 35, FI-40014 Jyväskylä, Finland

A R T I C L E I N F O

Article history:
Received 24 August 2012
Received in revised form
18 September 2013
Accepted 13 October 2013

Keywords:
Multiple criteria analysis
Remote monitoring
SMAA
Heat, power and water consumption
Municipal buildings

A B S T R A C T

Conservation of natural resources drives municipalities to monitor their heat, power and water consumption more accurately. The objective of this study was to evaluate different implementation possibilities for remote monitoring systems for the municipal buildings of two medium-sized municipalities, Hollola and Nastola in Southern Finland. Four different alternatives were considered: (1) a system by an external service provider, (2) a system provided by the local energy distribution company, (3) a system built by the municipalities themselves, and (4) using the current manual system but with more frequent data collection. The alternatives were evaluated in terms of multiple functional, operational, and economical criteria and compared considering different preferences for the criteria. Stochastic Multicriteria Acceptability Analysis (SMAA) was used in comparing the alternatives. SMAA is a method for aiding multicriteria group decision-making in problems where both criteria measurements and decision makers' preferences are uncertain, imprecise or partially missing. The analysis resulted in recommending the remote monitoring system by an external service provider.

1. Introduction

Monitoring is a corner stone in reducing the consumption of water, heat and power in buildings. Measuring and making the consumption visible for people allows and encourages them to use natural resources sparingly [12,20,27,60]. Monitoring also allows municipalities and other property owners to identify buildings that consume notable amounts of energy or water. In this paper, we focus on smart metering and remote monitoring systems for municipal buildings, where the consumption structure differs from homes and office buildings [11].

Monitoring serves several purposes in municipal property maintenance. First of all, technical personnel can prioritize municipal buildings based on their energy consumption and start improving buildings' energy efficiency based on this priority. Secondly, real-time monitoring makes it possible to follow the indoor temperature of buildings and to control the settings to maintain optimal temperature in different kinds of buildings. Thirdly, measurements can indicate a need for building renovation and also verify the effect of realized renovations on the energy efficiency. Such renovations may include improved insulation, heat recovery and utilizing e.g. solar or geothermal heat [26]. Smart metering enables in the future controlling the energy consumption of buildings based on variable electricity price [22]. In case buildings produce more energy than they consume (zero-energy and energy-plus buildings), smart meters are used for measuring the hourly energy balance and for authenticating the amount of energy supplied into the grid. All the above-mentioned functionalities help municipalities to improve and economize their property management as well as their energy balance and costs.

Remote monitoring is a quickly spreading technique that helps monitoring and reducing consumption of heat, power and water in buildings [4,43]. The objective of this research is to assist the choice of remote monitoring systems for two medium-sized municipalities, Hollola and Nastola located in the Päijät-Häme region in Southern Finland, some 100 km north of Helsinki. In 2009 the number of inhabitants was 21,793 in Hollola and 15,048 in Nastola. This study bases on the IMMU project "Local Action to Prevent Climate Change" (2009–2011), which aims to reduce greenhouse gas (CO_2) emissions of Finnish municipalities [19]; and the AsEMo project "Monitoring Eco-Efficiency of Residency" (2008–2010) coordinated by the Aalto University [2]. The AsEMo project studies and develops smart metering systems and services for buildings for the needs of different stakeholders from inhabitants to energy companies.

This study compares different alternatives for monitoring the heat, power and water consumption in municipal buildings, such

* Corresponding author. Tel.: +358 40 5767838.
E-mail address: pekka.o.salminen@jyu.fi (P. Salminen).

0378-7788/$ – see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.enbuild.2013.10.037

as schools, sports facilities, day-care centers, health-care units [46]. This kind of problem setting is a typical multicriteria decision problem. Four different decision alternatives were evaluated in terms of 10 main criteria, each of which consisted of 2–15 technical or functional sub-criteria. The sub-criteria were evaluated by experts during this study and their relative weights within each main criterion were assessed by representatives of the municipalities [46]. Such subjectively assessed evaluations must be considered imprecise. Assessment of the relative importance of the main criteria was more difficult because not all interest groups could participate in this phase of the process. For this reason, no weights were available for the main criteria.

The choice of the multicriteria method depends on the characteristics of the problem. The most common multicriteria decision support methods can be classified into multi-attribute utility/value theory (MAUT/MAVT) based methods [25], outranking methods such as ELECTRE [47] and PROMETHEE [3], and pairwise comparison methods, such as the Analytical Hierarchy Process (AHP) [48]. These methods cannot be directly applied in the current problem, because criteria measurements are imprecise and preference information for the main criteria is missing. The outranking methods require extensive preference information in form of various thresholds for each criterion (indifference, preference and veto thresholds), and also weights for the different criteria. Pairwise comparison methods require the DMs to perform an impractically large number of comparisons in large problems. General MAUT requires assessment of a potentially non-linear utility function in multiple dimensions. For this reason, linear MAUT/MAVT is of the applied in real-life problems. However, even linear MAUT/MAVT requires complete preference information in form of trade-off weights, which were missing in the current problem. The first multicriteria method to handle missing preference information was the comparative hypervolume criterion method [6], which was based on computing for each alternative the volume of the multi-dimensional weight-space that makes the alternative the most preferred. However, this method was restricted to deterministic criteria measurements. For these reasons, we apply here the Stochastic Multicriteria Acceptability Analysis (SMAA) method, which is a MAUT/MAVT-based method that can be used with imprecise criteria measurements when preference information is imprecise, uncertain or missing.

SMAA can be applied for selection, classification and ranking problems in different application areas. Earlier successful real-life applications of SMAA include e.g. developing the Helsinki General Cargo Harbor [17], choosing the implementation order of the general plan of Kirkkonummi [16], evaluating alternatives in a technology competition for cleaning polluted soil in Helsinki [18], locating the South-Karelian solid waste treatment facility [37], choosing among waste storage alternatives for Pietarsaari multi-fuel bio-CHP plant [33], choosing the land-fill reparation method at Huuna [38], forest ecosystem management [23], strategic planning of an electricity retailer [41], choosing elevator systems for office buildings [56], risk-based classification of nano-materials [58], locating an airport hub for centralizing cargo in Morocco [42], and decision-making in drug benefit-risk analysis [59]. This paper introduces the first application of SMAA for choosing an energy monitoring system of buildings. In earlier SMAA-applications, criteria were not organized as a hierarchy. Therefore SMAA was extended in this application to treat a two-level criteria hierarchy.

The SMAA methods handle imprecise, partly missing, or conflicting weight information by exploring the weight space in order to describe what weights, if any, make an alternative most preferred. During the analysis, both criteria measurements and weights are constrained by their distributions. Related simulation approaches for analyzing multicriteria problems with different kinds of incomplete information include, for example, those by Stewart [50–52], Butler et al. [5], Durbach and Stewart [10], García et al. [14], and Jiménez et al. [21]. A recent case study of applying multicriteria analysis on energy solutions for buildings under uncertainty is presented by Wang et al. [63].

Different variants of SMAA exist. In the original SMAA method by Lahdelma et al. [29] the analysis was performed on the basis of an additive utility or value function and stochastic criteria data to identify for each alternative the weights that made it most preferred. SMAA-2 by Lahdelma and Salminen [35] generalized the analysis to apply a general utility or value function, to include various kinds of preference information and to consider holistically all ranks. The SMAA-O method [32] extended SMAA-2 for treating mixed ordinal (qualitative) and cardinal criteria in a comparable manner. The Ref-SMAA and SMAA-A methods [7,8,34] compare the alternatives by applying Wierzbicki's achievement scalarizing functions. Different ways to represent dependent uncertain criteria are presented in Lahdelma et al. [30,31]. Recent developments include SMAA-P [36] based on the piecewise linear prospect theory, SMAA-TRI [55] for sorting problems, and an application of SMAA for descriptive decision analysis [9]. The efficient implementation and computational efficiency of the SMAA methods have been described in Tervonen and Lahdelma [57]. Refer to Tervonen and Figueira [54] and Lahdelma and Salminen [39] for surveys on different SMAA methods and applications.

This paper is organized as follows: Section 2 introduces a general remote monitoring system for monitoring residential heat, power and water consumption. Section 3 formalizes the problem of choosing a municipal remote monitoring system in terms of alternatives, criteria measurements, and weights. Section 4 describes the applied SMAA method. Section 5 presents the analysis results and compares the results with MAVT and AHP. Section 6 discusses the potential impact of the remote monitoring system, use of SMAA in this problem, and the future phases of the decision process. Section 7 contains the conclusions.

2. Advanced metering infrastructure

Remote monitoring of heat, power and water consumption means that the consumption measurements are transferred automatically from meters to a centralized measurement database. This makes it possible to monitor accurately and almost in real-time the consumption of electricity, heat and water in buildings [15]. The concept of an integrated remote monitoring system is illustrated in Fig. 1.

Automatic Meter Reading (AMR) includes smart meters, metered data collectors and meter reading units. Smart meters for measuring heat, power or water consumption of buildings and are increasingly common today. Smart meters transfer data to the metered values data base (MVDB) via the meter reading unit. Typically the meter reading unit gathers data from several metering sensors that are installed in the building. Smart meters send pulse or digitally registered data to data collector(s) at e.g. 1 h intervals. In the MVDB data is analyzed according to monitoring needs. Monitoring enables user to identify changes in buildings' (or apartments') energy and water consumption, compare consumption levels between various buildings (or apartments) and receive alerts, when consumption exceeds a set limit. Energy and water consumption can be monitored at different time resolutions, anything from once per minute to once per year [62].

An Advanced Metering Infrastructure (AMI) is designed to serve two-way and machine-to-machine communication. The AMI network performs a variety of intelligent metering tasks such as consumption metering, power quality monitoring and (optionally) load control activities [26]. An advanced smart meter can also act as an energy service interface that allows private networks to