Sustainable Cities and Society 35 (2017) 289–297

Contents lists available at ScienceDirect

Sustainable Cities and Society

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

Multicriteria evaluation of sustainable energy solutions for Colosseum

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A R T I C L E I N F O

Keywords:
Sustainable energy planning
Energy efficiency
Heating systems
Buildings
Multicriteria decision analysis
Stochastic multicriteria acceptability analysis

A B S T R A C T

Colosseum is a large office building in the capital region of Finland. The building owner operates on the highly competitive office rental market. With increasing emphasis on environmental responsibility, energy efficiency and sustainable energy solutions can provide competitive edge on the rental market. This study evaluates in terms of multiple criteria different alternatives to enhance the energy solutions of the building. The alternatives included different configurations of solar power, ground source heat, and roof constructions, along with district heating. Decision criteria included internal rate of return, energy efficiency, CO2 emissions, and attractiveness. Attractiveness was evaluated by a set of experts in office building valuation. The alternatives were compared using Stochastic Multicriteria Acceptability Analysis (SMAA), which is a simulation based method for decision problems where different kinds of uncertain information are represented by probability distributions. As novelty, the pairwise winning indices were used to form a stochastic ranking of alternatives. Analyses were conducted both without and with decision maker's preference information. Most preferred alternatives were based on ground source heat. However, these alternatives require extensive renovation to install a hydronic central heating system. If such renovation is considered infeasible, then solar power alternatives become most preferred.

1. Introduction

According to the Paris Agreement, Finland is committed to reducing its greenhouse gas (GHG) emissions by 40% by year 2030 (EU, 2016). About one third of the Finnish GHG emissions are caused by energy consumption in buildings (Vehviläinen et al., 2010). Because the renewal rate of the building stock is very slow, it is also necessary to improve the energy efficiency and GHG emissions of existing buildings. Renovation and extension of the life span of existing buildings is also cheaper for the building owner and causes less harm for the environment compared to tearing down and building a new building.

The target of this study is Colosseum, which is a large office building in the capital region of Finland. It was built in 1988 to serve as the main office for Imatran Voima Ltd. (currently Fortum Ltd.), which is a major power company in Finland. Currently the building owner is operating on the office rental market. Although the building is today mostly heated with district heating (DH), it has a historical reputation of consuming a lot of electric power. DH is still supplemented by direct electric heating. This image makes it difficult to find long-term tenants and to maintain a high degree of utilization for the building. The current utilization degree for Colosseum is 81%. During recent years, some energy efficiency improvements have already been implemented. However, further sustainability improvements can make the building more attractive for tenants (Fig. 1).

In this study, we evaluate several different alternatives for improving the sustainability of Colosseum. The decision maker (DM) is the building owner. The alternatives include, along with DH, different configurations of solar power, ground source heat, and roof construction for the inner courts. The decision between the different alternatives must consider several local conditions and objectives. In this case the decision criteria include internal rate of return, energy efficiency, CO2 emissions, and attractiveness of the building on the office rental market. Therefore, we apply multicriteria decision analysis (MCDA) in this study. MCDA methods support evaluating and comparing alternatives in terms of multiple non-commensurate criteria.

MCDA methods have recently become widely employed in sustainable energy planning problems. Recent building level studies of MCDA for heating and cooling systems include e.g. Chinese, Nardin, and Saro (2011), Sun, Huang, and Huang (2015), Wang (2015), Chen and Pan (2016), Lee, Pourmousavian, and Hensen (2016), Seddiki, Anouche, Bennadji, and Boateng (2016), Gupta, Anand, and Gupta (2017), Niemelä, Levy, Kosonen, and Jokisalo (2017). Recent community level

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http://dx.doi.org/10.1016/j.scs.2017.07.019
Received 17 May 2017; Received in revised form 14 July 2017; Accepted 29 July 2017
Available online 12 August 2017

Fig. 1. Colosseum, Vantaa, Finland (ELO, 2016).

MCDA analyses include e.g. Catalina, Virgone, and Blanco (2011), Grujić, Ivezić, and Živković (2014), Ghafghazi, Sowlati, Sokhansanj, and Melin (2010), Kontu, Rinne, Olkkonen, Lahdelma, and Salminen (2015), Neves, Leal, and Lourenço (2015), and Stamatakis, Mandalaki, and Tsoutsos (2016). Reviews about using MCDA methods for sustainable energy planning can be found in Pohekar and Ramachandran (2004), Wang, Jing, Zhang, and Zhao (2009), Si, Marjanovic-Halburd, Nasiri, and Bell (2016), Kumar et al. (2017) and Mardani et al. (2017). A recent survey about single and multiobjective optimization approaches in sustainable energy planning problems is presented by Sameti and Haghighat (2017).

In this study we applied Stochastic Multicriteria Acceptability Analysis (SMAA), which is an MCDA method suitable for problems where information is imprecise, uncertain, or partially missing (Lahdelma & Salminen, 2001). SMAA has earlier been applied in several sustainable planning problems, such as municipal planning (Hokkanen, Lahdelma, Miettinen, & Salminen, 1998), harbor development (Hokkanen, Lahdelma, & Salminen, 1999), cleaning polluted soil (Hokkanen, Lahdelma, & Salminen, 2000), siting waste treatment plant (Lahdelma, Salminen, & Hokkanen, 2002), forest management (Kangas, Hokkanen, Kangas, Lahdelma, & Salminen, 2003; Kangas, Kangas, Lahdelma, & Salminen, 2006), risk-based classification of nanomaterials (Tervonen et al., 2009); multimodal cargo hub development (Menou, Benallou, Lahdelma, & Salminen, 2010), strategic environmental assessment (Rocchi, 2012), rural electrification in developing countries (Rahman, Paatero, & Lahdelma, 2013), assessing energy policy (Rahman, Paatero, Lahdelma, & Wahid, 2016), choosing energy monitoring systems (Pesola, Serkkola, Lahdelma, & Salminen, 2014), evaluation of combined heat and power units (Wang, Jiao, Lahdelma, Zhu, & Zou, 2015), air quality assessment (Ari, Ozkose, & Gencer, 2016), water planning and management (Linhoss & Ballweber, 2015; Zheng, Egger, & Lienert, 2016), dredged material management (Scheffler, Roth, & Ahlf, 2014), and evaluating residential heating alternatives (Kontu et al., 2015).

This study is the first case of applying SMAA on evaluating sustainable energy solutions for a building. For the building owner the main contribution of this study was to extend traditional benefit-cost analysis with explicit consideration the ‘soft’ attractiveness criterion. A theoretical novelty of this study was to apply *pairwise winning indices* of SMAA for producing a stochastic ranking of the alternatives.

In the following, we describe the problem, the SMAA method, and the results of the analysis followed by discussion and conclusions.

2. Decision problem

2.1. Colosseum

Colosseum is an office building located at Vantaa, in the capital region of Finland. The floor space of the building is 56,000 m^2. The building is mainly heated by DH through ventilation air. In the Finnish system, DH is also used for producing hot tap water. Total annual DH consumption for the building is 3900 MWh. To maintain good thermal comfort, electric radiators are placed under windows. During the cold season the radiators consume about 1000 MWh. In addition, cooling the building in the summer consumes 560 MWh. Price of electric power is about 90 €/MWh and price for DH is about 45 €/MWh. As a result, the yearly overall energy costs for the building are 700,000–800,000 €, which are divided between power and DH in 70%/30% ratio. Both for economic and sustainability reasons it is desired to minimize power consumption.

During recent years, some energy efficiency improvements have already been implemented in order to reduce electricity consumption while maintaining good indoor air quality. The completed improvements include sealing windows, renewal of ventilation and cooling systems, and changing indoor and outdoor lighting to LEDs.

The current vacancy rate for Colosseum is 19%. The building owner expects that further sustainability improvements can make the building more attractive for tenants. Therefore the goal of this study is to evaluate and choose among different feasible sustainable energy solutions for Colosseum.

2.2. Feasible sustainable energy solutions

Basic sustainable energy solutions for Colosseum include on-site carbon-neutral production, further improvement of energy efficiency, and replacing electric heating by DH. On-site production alternatives that were initially considered included solar power, ground source heat pump, small scale wind power, biofuel combustion, and small scale combined heat and power (CHP) production using fuel cells.

Based on preliminary analysis, wind power, biofuel combustion and fuel cells were excluded. Wind power is not well suited in an urban environment, local wind conditions are not good, and cost efficiency of small scale wind power is currently inferior to solar power. Biofuel combustion was considered unsuitable, because it requires extensive fuel transports, large fuel storage, and cost efficiency is inferior to ground source heat. Fuel cells were excluded, because the technology is still in the development stage, and the investment costs are very high.

Different solar power alternatives were considered. The yearly sum of solar radiation in Southern Finland is about 1100 kWh/m^2 on optimally-inclined south-oriented PV panels (Motiva, 2016a). This is same order of magnitude as in Baltic countries and Denmark. However, the coincidence of PV production and power demand is a little worse in Southern Finland due to more northern location (60–61°N). Finland does not have a special feed-in tariff for solar power. This means that it is not profitable to produce solar power in excess to own demand. Based on metering information, the base load of electric power for the building is about 410 kW. However, the restricting factor for solar power in this building will be available space.

Solar panels can be installed both on the rooftop and on the façade. For solar panels on the planar roof, the tilt angle and area were optimized. Greater tilt angle increases the annual production per panel, but reduces the panel area that fits on the roof. At greater tilt angle panel rows must be installed further apart to prevent shading. Greater tilt angle also increases the wind load requiring more expensive roof and panel support constructions. As result of optimization, tilt angle 15° was selected for the rooftop panels. The façade panels must be installed at