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Life cycle based dynamic assessment coupled with multiple criteria decision analysis: A case study of determining an optimal building insulation level

Joshua L. Sohn [a], Pradip P. Kalbar [b, *, 1], Morten Birkved [b]

[a] Roskilde University, Department of Environmental, Social and Spatial Change, Roskilde, Denmark
[b] Quantitative Sustainability Assessment Division, Department of Management Engineering, Technical University of Denmark (DTU), Produktionstorvet 424, DK-2800 Kgs. Lyngby, Denmark

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ABSTRACT

This work looks at coupling Life cycle assessment (LCA) with a dynamic inventory and multiple criteria decision analysis (MCDA) to improve the validity and reliability of single score results for complex systems. This is done using the case study of a representative Danish single family home over the service life of the building. This case study uses both the established and the coupled MCDA assessment methods to quantify and assess the balance of impacts between the production of mineral wool insulation versus the production of space heat. The use of TOPSIS method for calculating single scores is proposed as an alternative to the ReCiPe single score impact assessment method. Based on the single score impact values obtained from both of these methods, various insulation levels are ranked to determine an ideal insulation level and gauge the effectiveness of environmental impact reduction measures in current Danish building regulations. Using a comparison of the results from the two methods, a preferred choice of impact assessment method is determined. The findings show that if the midpoint impacts for a particular scenario are strongly correlated with a climate change impact indicator, it does not matter which impact assessment is applied. However, for the scenarios where other impact categories vary inversely or independently from the climate change impact indicator, such as with renewable energy production, there is need for a more unconventional method, such as the TOPSIS method, for calculating single score impacts.

1. Introduction

In Denmark, there are nearly 1.2 million single family detached houses (SFDH) making up approximately 45% of all dwelling units (Klintefelt, 2016). These houses use over 76 PJ of energy annually, and approximately 63% use district heating, with district heating accounting for nearly 37% of total residential energy use (Energistyrelsen, 2014). While these numbers do not represent a huge global impact potential, in other countries the market is much larger and SFDH can make up an even larger proportion of the national building stock, such as in the US, where SFDH make up over 63% of all dwelling units (EIA, 2009). Overall, the heating of houses, in particular single family homes, accounts for major global health, environmental and economic impacts. While space heating is necessary in most all houses, insulation also plays a key role in keeping a house warm by minimizing heat losses. This poses the challenge of determining an optimized balance between the provision of heat and application of insulation to achieve a defined level of livable condition (around 20 °C).

Over the last several decades, regulations have shifted toward requiring much higher levels of insulation (Papadopoulos, 2005). The result of this increased usage of higher levels of insulation has led to study of the emergy impacts of increased insulation levels such as that by Gustavsson and Joelsson (2010). In much of Northern Europe, mineral wool insulation has a major market share, and it has lower environmental impacts than other common insulation materials (Schmidt et al., 2004). There have been studies

* Corresponding author. Quantitative Sustainability Assessment Division, Dept. of Management Engineering, Technical University of Denmark (DTU), Produktionstorvet Building 424, Room 231, 2800 Kgs. Lyngby, Denmark.
E-mail addresses: kalbar@iitb.ac.in, pradipkalbar@gmail.com (P.P. Kalbar).
[1] Present affiliation: Centre for Urban Science and Engineering, Indian Institute of Technology Bombay, Powai, Mumbai 400 076, India.

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of the impacts of varying types of insulation completed in the past, such as the LCA carried out by Schmidt et al. (2004) and another by Pargana et al. (2014) who compared the impacts of varying types of insulation based on a functional unit of a specified thermal resistance for a specified area. Additionally, Kaynakli (2012) assessed varying levels of insulation for use in buildings based on life cycle cost, and Mazor et al. (2011) assessed the life-cycle green house gas effects of applying rigid insulation to a building. Furthermore, the study undertaken by Gustavsson and Joelsson (2010) relied on whole buildings as case studies for impact assessment of varying types and levels of insulation applied to varying building typologies. However, none of these indicate an optimal level of insulation for residential buildings and none of these account for the dynamic nature of the energy mix that supplies space heat to buildings throughout their service life, nor do any of these apply and compare multiple impact assessment methods, all of which are done in this study.

In Denmark, while there has been greater recognition of the need for insulation, there has also been a significant shift toward 'greener' and less impactful energy production. DEA (2011) reports that such a continuous improvement in the energy production has been planned. In the context of prevailing global warming crises, this type of change in energy production is also possible, if not also likely, on the global scale (Asif and Muneer, 2007). Because of the potential for global human health and environmental impacts of either over or under insulating, an assessment of a broader spectrum of impact categories is necessary.

Sohn et al. (2016) in their recent study, on assessing balance of insulation material and heat required for Danish reference building, have highlighted this shift and its effect on determining optimal levels of insulation. However, Sohn et al. (2016) base their conclusions only on climate change indicator. It is widely recognized that climate change potential is not always indicative of total environmental impact (Laurent et al., 2010; Hauschild et al., 2013). Hence, there is a need for assessing the balance between insulation material and heating of building covering all impacts on the environment, human health, and resource depletion.

Thus, one of the primary areas of focus of this study is adding robustness to previous findings, such as those in Sohn et al. (2016), regarding optimal levels of insulation for residential construction in Denmark by extending the research to incorporate all environmental impacts for the purpose of decision-making. This determined optimum level is intended to both inform policy makers, in order to improve regulations, as well as to inform the producers of mineral wool insulation, in terms of areas of potential improvement in the production process. This is done through the incorporation of MCDA.

Within the LCA community, however, there is significant adherence to the use of certain standard characterization, normalization and weighting methods, such as the ReCiPe single score. Nevertheless, in this study, we provide evidence to indicate that these single scores might not always produce valid results pointing to correct decision support. Hence, in this paper, we assess multiple insulation levels using two Life Cycle Impact Assessment (LCIA) methods coupled with Multiple Criteria Decision Analysis (MCDA). This allows for the generation of two single score assessments, one based on ReCiPe endpoints and the other derived from MCDA of midpoint impacts, which are used to rank the insulation scenarios.

In doing this, we evaluate the use of presently utilized and established assessment methods (climate change potential and single score) and the MCDA method, which we propose as an alternative, for the assessment of optimal insulation levels and also determine the factors that might impact such assessment. This multi-pronged approach allows for a better gauge of the appropriate use of these varying assessment methods for future implementation in LCA of durable materials, and in particular it gives a holistic indication of the effectiveness of the proposed changes in Danish building regulations.

2. Methodology

This work uses a novel approach of coupling dynamic assessments based on LCA with MCDA. LCA is used to assess the impact of various insulation levels and energy necessary to fulfill the heating requirements of the living space in the buildings. The results from the LCA are subsequently used to derive single scores. One single score is derived in accordance with established impact assessment methods, while for the second single score method we introduce a new approach for aggregating impact indicators using MCDA. A comparison of these two methods is shown in Fig. 1. These are both also compared to a simplified impact assessment using climate change potential as an indicator for all impacts. The following sections describe this method in further detail.

2.1. Life cycle assessment

One of the components used in this work is life cycle assessment, which is applied with the goal of determining an optimal level of mineral wool insulation for average SFDH in Denmark. To do this, a functional unit was defined as 'reference house heated for 50 years'. The 'reference house', a single storey detached home with a gross heated floor area of 151.2 m^2, is further described by Sohn et al. (2016). This functional unit represents a trade-off between the materials necessary to insulate, including major incremental building materials, and the energy required for heating the building with the specified amount of insulation over the course of the building's 50-year service life. The system for this assessment includes the production of insulation and related incremental building materials and their transport, as well as the production and transport of the energy used in the provision of space heating.

In addition, we have modeled a Danish heat mix based on projections for the future Danish energy supply. This modelling effort allows for a better representation of the dynamic nature of the heat mix and associated future impacts of providing heat than could be achieved with the use of a static energy mix based on the current energy market (Sohn et al., 2016). In the LCA model, the energy provision required to fulfill the functional unit was based on a heat loss model suggested for use for Danish SFDH (Aggerholm and Sørensen, 2011; Sohn et al., 2016). Further details on the heat loss modelling and the LCA methodology that were used in this work can be found in Sohn et al. (2016).

In this study, two quite different methods were used for impact assessment to cover the different uncertainties associated with methodological choices. ILCD 2011, which provides only midpoints, is the first impact assessment method (EC, 2010). The second impact assessment method used in this study was ReCiPe method (Goedkoop et al., 2013). The ReCiPe method provides both midpoint (potentials) and endpoint (damages) impact levels. The ReCiPe endpoints are further normalized and then aggregated into a single score. This was done for three cultural perspectives, hierarchist, individualist, and egalitarian as well as a further three weightings based on the endpoint results derived relying on the hierarchical cultural perspective: equal weighting, emphasis on human health, and emphasis on ecosystem (i.e. environmental impacts), which are detailed in Supplementary information (SI) I Part 1. All the product system modelling and impact assessment hereof was carried out in OpenLCA version 1.4.1 (Green Delta, 2015).