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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. (2017) 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. (2017) 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. (2017), 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. (2017). 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., 2017). 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., 2017). Further details on the heat loss modelling and the LCA methodology that were used in this work can be found in Sohn et al. (2017).

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).

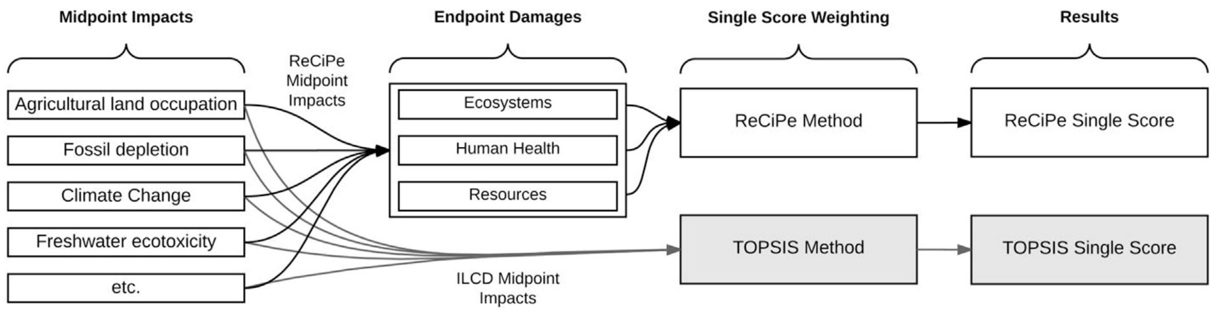

Fig. 1. Comparison of ReCiPe and TOPSIS MCDA analytical methods.

2.2. Multi-criteria analysis

Many methods in MCDA are available that can be used to process midpoint impact indicators and obtain a single score. The most commonly used methods are Simple Weighted Sum Method (WSM), AHP, PROMEETHE, Compromise Programming, and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Figueira et al., 2005; Hwang and Yoon, 1981; Yoon and Hwang, 1995). We employed TOPSIS for obtaining single scores based on ILCD midpoints, because of the wide applications of TOPSIS for similar problems and the mathematical approach used in TOPSIS (Behzadian et al., 2012; Kalbar et al., 2015, 2012).

TOPSIS works by selecting the best alternative from a group of scenarios, each having been evaluated against a set of criteria. In this study, the insulation and heat provision scenarios are assessed based on ILCD midpoint impacts. Each impact is then weighted, based on different weighting schemes (refer to Tables SI I.1 and I.2 in SI I, Part 1). Based on the input of evaluated scenarios, TOPSIS then generates two artificial scenarios, an ideal alternative (the best possible idealized scenario i.e. in this case, the scenario with lowest possible midpoint impacts) and a negative ideal alternative (the worst possible idealized scenario i.e. in this case, the scenario with highest possible midpoint impacts). All other scenarios are then measured against these two idealized scenarios, and each scenario is assigned a score based on the relative closeness to the ideal alternative and distance from the negative ideal scenario. More details on the methodological details can be found in Hwang and Yoon (1981), Yoon and Hwang (1995) and Kalbar et al. (2012).

2.3. Building insulation levels and heat energy scenarios

In the present study we have focused primarily on a hypothetical reference house constructed in 2015 which is heated throughout its 50-year service life (2015–2065) using the Danish heat mix (this scenario will be referred to hereafter as the 2015-mix scenario). As previously mentioned we have considered the dynamic nature of the heat grid mix, integrating a linear interpolation of the projected heat mix available from 2015 to 2050 (Rasmussen, 2012) for 2050–2065. However, to observe the sensitivity in the results we have also created the following hypothetical heat energy supply scenarios.

1. Building constructed in 2015 and heated with energy obtained using only solar energy (2015 – Solar scenario)
2. Building constructed in 2015 and heated with energy obtained using only wind energy (2015 – wind scenario)
3. Building constructed in 2015 and heated with energy obtained using only nuclear energy (2015 – nuclear scenario)
4. Building constructed in 2015 and heated with energy obtained using only hydro energy (2015 – hydro scenario)

Ten insulation scenarios (IS) were tested using these 4 alternative energy scenarios and the 2015 dynamic energy mix. The IS were developed based on a linear increase of insulation thickness (and total mass) in accordance with the three regulatory levels of insulation present in the Danish Building Regulations, BR10 (DEV, 2010). These insulation levels range from a level that represents a minimally insulated home (IS1) to a super-insulated home (IS10), these are outlined in Table 1 and are further detailed in previous work by Sohn et al. (2017).

3. Results and discussion

This study was undertaken because, while climate change potential was used in a previous study by Sohn et al. (2017), there were other midpoint impact indicators that exhibited trends that differed from the trends exhibited by the climate change impact potential (Sohn et al., 2017). This observation, that Sohn et al. (2017) made, is further evident from the midpoint impacts potentials obtained from the ILCD method as well as the midpoint and endpoint impacts potentials obtained from the ReCiPe method for all the five cases (i.e. 2015 Danish heat mix, 2015-solar, 2015-wind, 2015-nuclear, and 2015-hydro), which are provided in SI II, Table SI II.1–5. The results in these tables show that there is disagreement among the indicators regarding the optimal insulation scenario/insulation level. For example, as shown in Table SI II.1H, the results of the 2015-mix scenario in terms of climate change impact indicator identifies IS5 as the best insulation level. However, when using Freshwater Eutrophication as the critical indicator, IS7 is identified as the best insulation level. The next sub-sections discuss the results of the differing heat provision scenarios in detail.

3.1. 2015-Mix scenario

Single scores were obtained by further processing results from the ILCD method (midpoints) and directly from the ReCIPe methods (endpoints) for all ten scenarios for each of the weighing schemes. The ILCD midpoint impacts were processed using the TOPSIS method, which provided a score for each scenario, which we refer

Table 1
Description of insulation depths for IS1-10 (insulation scenarios) in accordance with Danish regulatory, BR10 (DEV, 2010), energy classification.

	Meets BR 2010[a]		Meets LE2015[a]					Meets BK2020[a]		
	IS1	IS2	IS3	IS4	IS5	IS6	IS7	IS8	IS9	IS10
wall	100	150	200	250	300	350	400	450	500	550
roof	200	275	350	425	500	575	650	725	800	875
floor	200	250	300	350	400	450	500	550	600	650

[a] Based on only building energy use calculations.

to as ILCD-TOPSIS single score. The endpoint impacts from the ReCiPe method were normalized and aggregated in order to obtain a single score. These scores were used to decide the ranks of each insulation scenario. The single scores (provided in SI I) and respective rank (shown in Fig. 2) were obtained using ILCD-TOPSIS method and ReCiPe method for each scenario.

The results in terms of ranks for the 2015-mix scenario are presented in Fig. 2, where the ranks of each IS for each respective weighting scheme are plotted as bars. Fig. 2 indicates that IS5 is the best insulation level if the 2015-mix scenario, which corresponds to the Danish district heating mix, is used. However, as we can see from Fig. 2, there is some disagreement between the ranks obtained by ILCD-TOPSIS single score and the ReCiPe single score. For example, when the egalitarian perspective is applied, IS3 insulation level is ranked at seven in accordance with the ReCiPe single score while the ILCD-TOPSIS method gives a rank of 5.

To further verify and analyze this disagreement between rankings, we plotted the internally normalized and weighted ILCD midpoints of the best alternatives identified by the ILCD-TOPSIS method and the ReCiPe method against the Positive Ideal Solution (PIS) in radar plots (see Figs. 3 and SI I, Part 2). In our case, PIS is the theoretically best scenario (i.e. theoretical scenario having lowest impacts). Fig. 3 shows these radar plots for the 2015-mix scenario. The scenario that most closely matches the shape of the PIS (shown in yellow fill with a black outline) is the best scenario from the ten IS under evaluation. As seen from these graphs, the disagreement varies according to cultural perspective and weighing scheme. Most importantly, the ReCiPe and ILCD-TOPSIS single scores tend to show agreement with climate change indicator in a considerable number of cases.

To investigate the nature of this agreement, i.e. whether it is due to the mathematical principles of the methods applied for aggregation of indicators or if it is because of a relation of climate change indicator with other impact categories, we considered four additional hypothetical scenarios. These additional scenarios are described in the methodology section. As these additional scenarios all are dependent on renewable energy, and hence less dependent on fossil energy, there is less correlation with climate change indicator than in the 2015-mix scenario. The results of this analysis are presented in next sub-section, 3.2. These results support the findings of the recent study by Kalbar et al. (2016), where, with the help of large empirical data set, it was shown that ReCiPe single score does not provide correct decision support.

3.2. Renewable energy scenarios

The radar graphs for the four renewable energy scenarios as applied with the 10 insulation scenarios are provided in SI II (See Fig. SI I.1A-X). These graphs show that for these scenarios, more disagreement appears between the ILCD-TOPSIS method and ReCiPe methods in the renewable energy scenarios. Figs. 4 and 5, which show plots similar to Fig. 2, illustrate greater disagreement between the ILCD-TOPSIS method and the ReCiPe method for 2015-nuclear and wind scenario respectively.

To further investigate the causes for such disagreement, contribution analyses for the IS5 2015-mix scenario and the IS5 2015-nuclear scenario were undertaken, as the nuclear scenario showed greater disagreement with the 2015-mix scenario than did the wind scenario. The results of the contribution analyses are provided in the SI I (Part 3, contribution analysis results), detailing two heating scenarios: the 2015 dynamic energy mix and the nuclear energy supply.

Fig. SI I.2 and SI I.3, show that mineral wool production process is the largest contributor across a majority of the impacts for both of the energy scenarios. However, based on an average across all ReCiPe midpoint impact categories, the contribution of mineral wool production in the 2015-mix scenario is 38% whereas in the 2015-nulcear scenario it is 59%. This finding suggests that impacts in the 2015-mix scenario are more dependent on climate change indicator, with the mineral wool production being entirely driven by fossil fuel consumption (Deutche Rockwool, 2012) and the Danish heat mix as represented in the 2015 dynamic energy mix also being more fossil fuel driven than that of the alternative fuel scenarios. In contrast, in the 2015-nuclear scenario other processes (primarily the nuclear energy production), which are not carbon driven, contributes 41% to all impacts. These observations suggest that the renewable energy scenarios overall impacts are less dependent on climate change indicator. This finding illuminates the

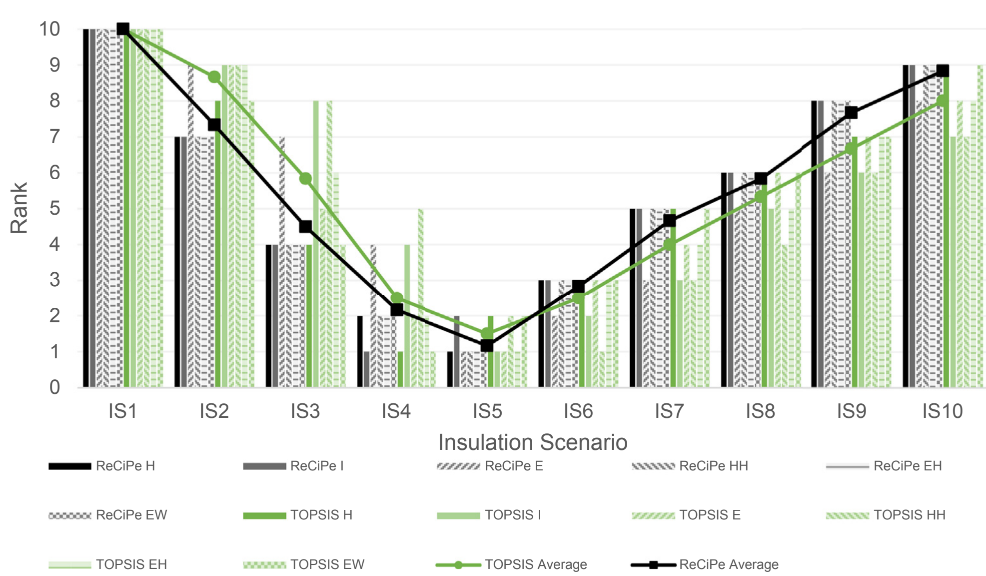

Fig. 2. Ranking in order from 1 (most preferable) to 10 (least preferable) for insulation scenarios 1–10 using district heating (2015-Mix energy scenario) based on ReCiPe and TOPSIS single score values for Hierarchist, Individualist, Egalitarian, Equal Weights, Higher weight to Human Health, and Higher Weight to Ecosystem perspectives and an average ranking based on all perspectives for both ReCiPe and TOPSIS analysis methods. Average lines showing overall agreement between the two analysis methods.

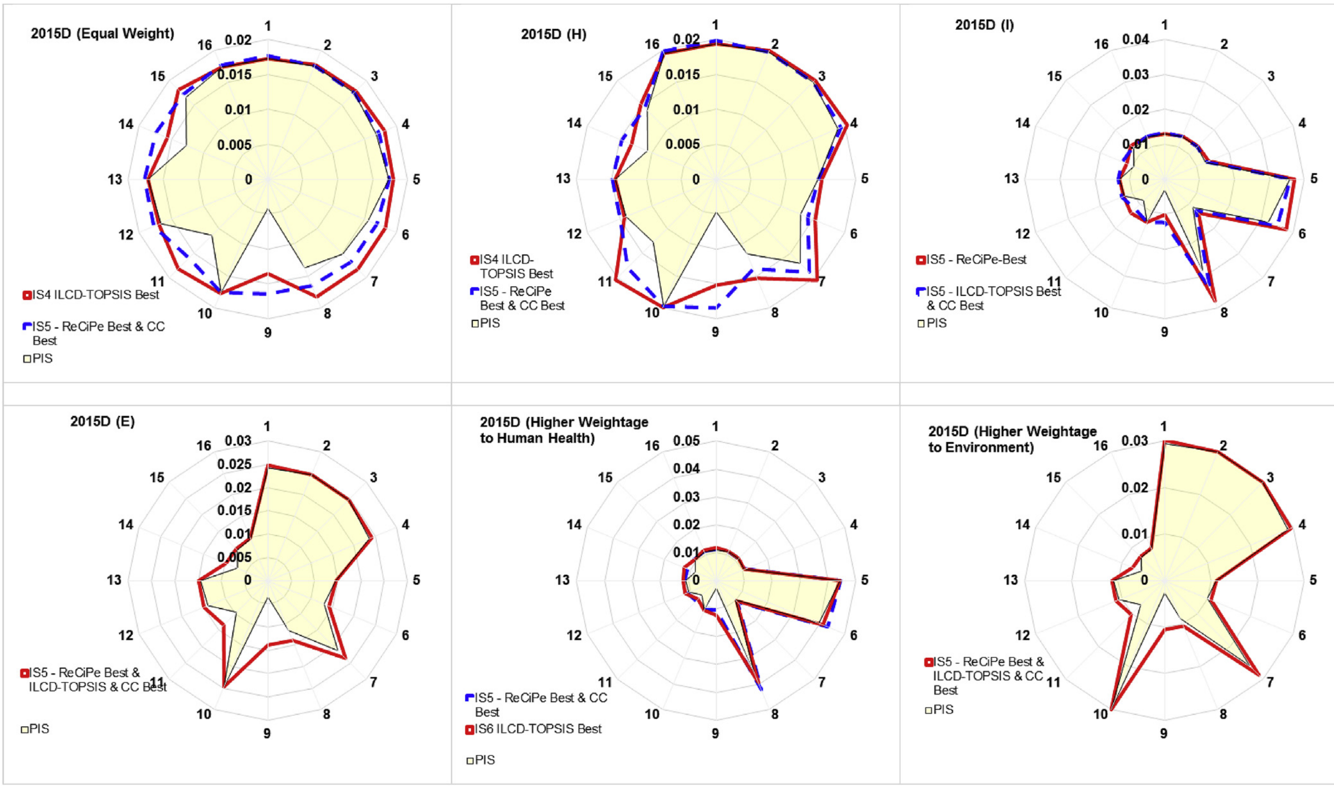

Fig. 3. Radar graphs showing the difference in the best identified scenario by the two single scores and climate change indicator for the three cultural perspectives (hierarchist, individualist, and egalitarian) and the three further weightings (equal weighting, emphasis on human health, and emphasis on ecosystem). PIS is positive ideal solution. 1: Acidification 2: Climate change 3: Freshwater ecotoxicity 4: Freshwater eutrophication 5: Human toxicity – carcinogenics 6: Human toxicity - non-carcinogenics 7: Ionizing radiation – ecosystems 8: Ionizing radiation - human health 9: Land use 10: Marine eutrophication 11: Ozone depletion 12: Particulate matter/Respiratory inorganics 13: Photochemical ozone formation 14: Resource depletion – mineral 15: Resource depletion - fossils, renewables and water 16: Terrestrial eutrophication.

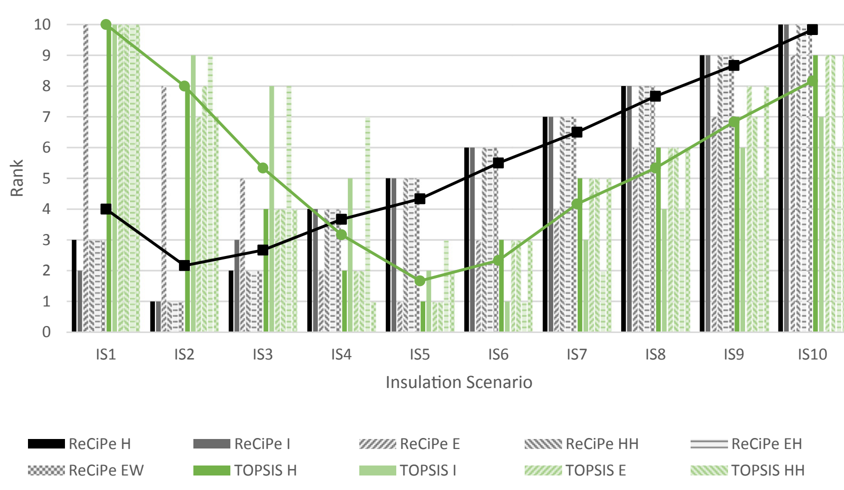

Fig. 4. Ranking in order from 1 (most preferable) to 10 (least preferable) for insulation scenarios 1–10 using nuclear energy heating based on ReCiPe and TOPSIS single score values for Hierarchist, Individualist, Egalitarian, Equal Weights, Higher weight to Human Health, and Higher Weight to Ecosystem perspectives and an average ranking based on all perspectives for both ReCiPe and TOPSIS analysis methods. Average lines showing overall disagreement between the two analysis methods.

disagreement between the TOPSIS method and single score results related with the influence of the climate change indicator on single score results both in ILCD and ReCiPe method in renewable energy scenarios. Thus, we see that lesser dependency on carbon fuels tended to create more variation in the midpoints (see midpoints results in Table SI II.1He5H in SI II). Such midpoints when aggregated into single score tend to disagree with the climate change indicator based ranks. For example, Fig. SI I.1 G-L, in SI I, showing radar plots for 2015-nuclear scenario, in each of these plots there is disagreement among climate change indicator, ReCiPe single score, and/or ILCD-TOPSIS methods. Similarly, disagreement among the methods is also found in the wind and solar energy scenarios. However, when we compare the radar plots for the 2015-mix scenario in Fig. 3, all six radar plots of different weighing schemes

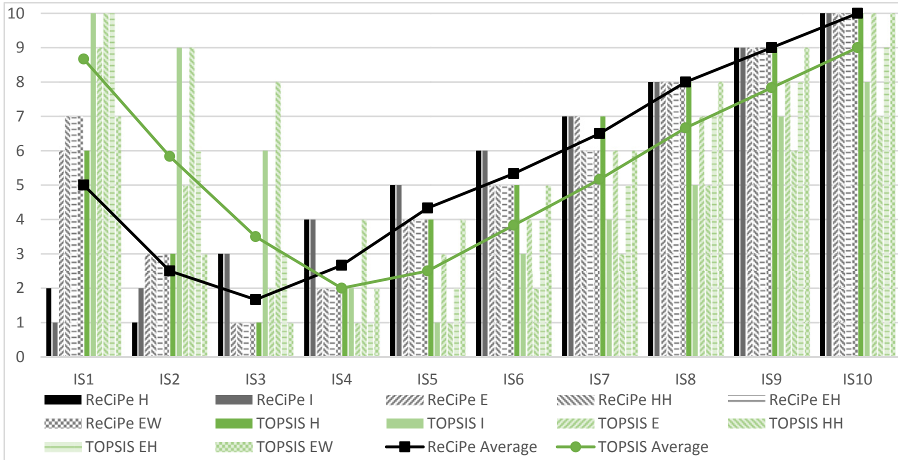

Fig. 5. Ranking in order from 1 (most preferable) to 10 (least preferable) for insulation scenarios 1–10 using wind energy heating based on ReCiPe and TOPSIS single score values for Hierarchist, Individualist, Egalitarian, Equal Weights, Higher weight to Human Health, and Higher Weight to Ecosystem perspectives and an average ranking based on all perspectives for both ReCiPe and TOPSIS analysis methods. Average lines showing overall disagreement between the two analysis methods.

climate change indicator based optimal IS level tend to match either the ReCiPe single score or with ILCD-TOPSIS based single score. This fits with the findings of Kalbar et al. (2016) that have shown with a hypothetical set of indicator data that ranks obtained by applying TOPSIS well represent weighting scheme chosen by LCA practitioner.

Fig. SI I.1G–L in SI I also present how the alternative identified by TOPSIS very closely matches the shape of PIS (marked by yellow fill with black outline) compared to those identified by the ReCiPe single score and climate change indicator. This shows that the application of the ILCD-TOPSIS approach can be used as a cross-validation of the results from other established methods such as the ReCiPe single score.

3.3. Areas of improvement for sustainable heating and insulation service for buildings

The contribution analysis reveals a primary area of improvement regarding the usage of fossil fuels in both the energy production and for mineral wool production processes. Such improvements are planned in Denmark for the heat energy mix, and as discussed in section 3.4 such improvements are not included in the results of this study. Furthermore, while production of mineral wool is one of the important potential area of improvement, in the context of a house constructed in the present (viz. 2015), future developments in mineral wool production are not relevant, as current production methods establish the impact of materials at the time of construction. This creates an offset in the impact profile, as the delay in impact for ongoing processes such as heat provision allow for technological improvements “along the road” to potentially reduce overall impacts. For the 2015 mix scenario, it isn't until 2036 that a house built according to IS1 would have a greater impact than a house built according to IS5, and it is not until 2048 that IS1 exhibits a greater impact than IS8 (Fig. 6). This gives a number of years for technological improvements in heat production before the greater total impacts of lower levels of insulation (such as IS3) are realized, potentially prolonging the payback time of greater levels of insulation. Additionally, should the service life of the building exceed 50 years, it seems likely, given the use of the 2015 dynamic energy mix with no further improvements after 2050 that IS8 could eventually become preferable to IS5, though such a preference would not be realized until more than several decades after the end of the assumed 50-year service life (see Fig. 6).

Given current research regarding the service life of buildings, an average service life of between 67 and 83 years could be assumed instead of the used 50-year service life (Thorsted and Østergaard, 2016). And, if we (very conservatively) assume no further improvement in the energy system after 50 years, for IS8 to be preferable, it would require an approximately 94-year service life. In such a case, an 83-year service life is not enough time for IS8 to become preferable. Furthermore, the assumption that no changes would be made to energy production in the years after 2065 is likely incorrect. Rather, it is likely that improvements would continue to be made to the energy mix, pushing the insulation production impacts payback point further in to the future. Thus, in the case of the service life necessary to make IS8 the optimal choice, and given current insulation production methods, the likelihood of improvements in energy production after 50-years from the present result in the conclusion that equal total impacts between IS8 and IS5 might never become practically attainable.

As previously described, the magnitude of the difference between the impacts of heating versus insulation can range from much greater (in the case of IS1) to much less (in the case of IS8). Unforeseen technological innovation or simple change in energy mix composition has the potential to greatly reduce the overall impact throughout the course of a buildings service life, as can be seen by comparing the absolute values for impacts from the varying energy mix scenarios (see SI II Table SI II.1–5). Conversely, the impacts of the insulation production are embedded at the time of construction and thus are not subject to change. Moreover, because the impacts of insulation production happen immediately at the time of construction, a decrease in the impact of production of insulation could with much greater level of certainty reduce the overall impact of an optimally insulated home. For example, if the impact of the production of insulation were reduced by 60%, making IS8 an optimal insulation level, the total impact of heating and insulating an optimally insulated reference house throughout its service life is reduced by over 35%, given the use of the 2015 dynamic energy mix (see Fig. 7 and Table SI II.3). With such a reduction in the impact of producing insulation, even the then non-optimally insulated IS5 would have over 31% lower impact for heating and insulation in relation to the optimally insulated house with present insulation production methods (IS5). In both of these cases there is a fixed reduction of the impact of providing insulation, whereas if that reduction was to be obtained through

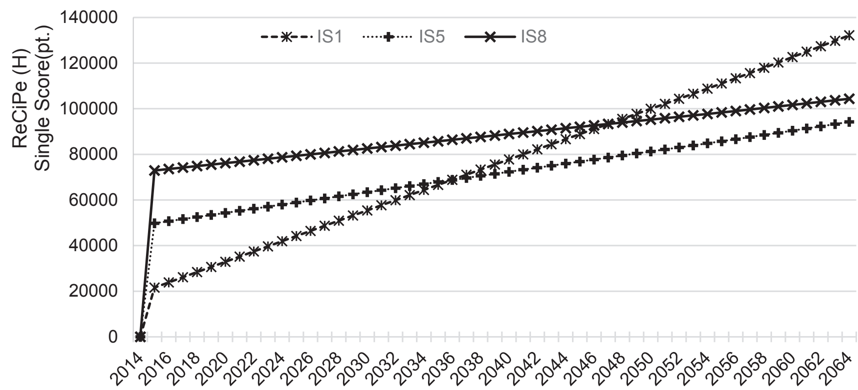

Fig. 6. Building impact (ReCiPe (H) single score) throughout the service life of the building for IS1, 5, and 8 recorded at the projected time of impact occurrence, assuming the use of a dynamic district heating mix following political projections.

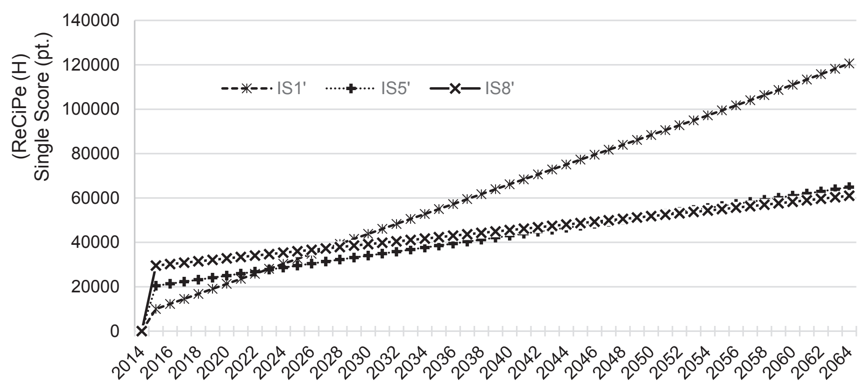

Fig. 7. Building impact (ReCiPe (H) single score) throughout the service life of the building for IS1, 5, and 8 recorded at the projected time of impact occurrence, assuming the use of a dynamic district heating mix following political projections with the impact of production of insulation reduced by 60%.

increased levels of insulation assuming a much greater service life (beyond 125 years), the level of uncertainty in obtaining the given reduction would be very high and the risk of much greater impact from unforeseen shortening of the service life of a particular installation of insulation in a building (i.e. from a fire) would be commensurably greater.

3.4. Limitations of the study

As the present study is an extension of the work reported in Sohn et al. (2017) all the limitations discussed in that study are also applicable here. The following are some of the specific limitations that need to be take into account while using the results from present study:

The dynamic energy mix used for calculation of the impacts of the district heating grid energy provision is, in practical application for the LCA conducted in this study, only partially dynamic. While the energy mix used for the 2015 dynamic energy mix heat supply scenario is 'dynamic' in so much as the mix of energy sources used to represent the Danish energy mix for assessment changes annually according to the energy mix projection, the processes used for provision of energy in the mix do not change in such a dynamic way. That is to say, the processes that use energy in the provision of heat, e.g. electric boilers and heat pumps, are modeled using a static energy supply that often includes a large fraction of coal and other fossil fuels. These processes were used because development of dynamic processes for all elements of the energy mix was deemed well beyond the scope of this study. However, implicit in the political plans for the development of the Danish heat-energy mix is also plans to reduce or eliminate fossil fuels from the energy mix in its entirety (DEA, 2011). The result of the use of these static processes in the dynamic energy mix results in a minor overestimation of the impact of providing heat, which becomes more apparent with time. However, this overestimation is much less than it would be if purely static energy mix were used, but it does represent a limitation of the study.

Also, the use of single score impact assessment was deemed necessary to account for the differing trends across impact categories, and TOPSIS was applied as a check on the ReCiPe single score results to help prevent over-prioritization of climate change impacts. However, individual impacts which may be of importance in specific geographical regions might still be missed if only relying on the single score assessment. Because of this, midpoint impacts should always be referenced in final decision-making. While not presented in the main body of the paper, the full results of the LCA including midpoint and endpoint impacts are included in SI II.

Furthermore, while it was deemed outside of the scope of the present work, the authors suggest that a full study of alternative fuels for the mineral wool production process could play a significant role in aiding companies and regulators in optimizing future insulation production and regulation.

4. Conclusions

The findings of this study were obtained in an attempt to answer questions regarding choice of impact assessment method via a case study attempting to answer three problems, viz., determining ideal insulation levels, gauging the effectiveness of environmental impact reduction measures in current Danish building regulations, and areas of potential improvement in mineral wool insulation production.

With regard to impact assessment method, our study shows that choice of impact assessment methods will yield different results, particularly when the impacts of the system are not dominated by fossil fuel driven processes. When the impact indicators are strongly related with the climate change indicator for all processes, it does not matter which method (i.e. ReCiPe single score or TOPSIS) is employed for determining best insulation level. This follows closely with previous findings regarding generalized assessments (Huijbregts et al., 2010). However, in more complex systems (i.e. when the processes include both impacts that are independent from climate change potential such as in renewable energy production and those that are dependent on climate change potential such as fossil fuel energy production), the findings of this study indicate that it is necessary to apply more sophisticated processing method for obtaining single score. This confirms the findings of Laurent et al. (2010) and Kalbar et al. (2017), that climate change indicator is not always indicative of overall impacts for complex systems. Thus, our study demonstrates the advantage of the TOPSIS method for obtaining single scores in cases where midpoint impacts do not all correlate well with climate change. The TOPSIS method proved to provide rankings commensurate with the applied weighting scheme.

Furthermore, in all assessments, the optimal insulation level indicated is below the insulation levels necessary to meet 2020 requirements when using only insulation to reduce energy consumption. And, the contribution analysis indicates that there are areas of improvement present in the process for production of mineral wool insulation. Primarily, a shift from the use of fossil fuels for process heat in the cupola furnace could have significant impact. However, given the likelihood that there will be more-reduced reliance on fossil fuels than indicated by the district heating production processes used in this analysis, it is likely that the impacts of heat production will also be reduced. The overall impact of these reductions indicate that only somewhat higher levels of insulation than presently required by Danish law could be beneficial in the future even if the impacts of the production of insulation were reduced. And, the magnitude of impact reduction necessary in the production of insulation to make superinsulation (IS8 or above) an optimal insulation level is unlikely. But, reduction in the impact of insulation production directly results in an overall reduction of the impact of heating and insulating residential homes, making it a good candidate for attempts to reduce the overall environmental impact of residential buildings in Denmark.

Because of this, from a whole-system perspective, the development of the process used for production of mineral wool insulation should be considered an important element for the overall reduction in impacts induced by new residential construction. This also indicates that building regulations could potentially be improved by including elements that account for the impacts of the insulation products used to fulfill the energy requirements. Such an inclusion could greatly reduce the overall environmental impacts from heating of house. And, due to its ability to account for the varied characteristics of the mid-point impacts found in complex systems, the inclusion of TOPSIS as a method of obtaining single score results in the assessments would be beneficial to the development of such regulations.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2017.06.058.

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