Journal of Cleaner Production 112 (2016) 275–281

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Life cycle inventory comparison of different building insulation materials and uncertainty analysis

Xing Su*, Zhong Luo, Yuhang Li, Chenhao Huang

HVAC&R Research Institute, School of Mechanical Engineering, Tongji University, Shanghai, 200092, China

ARTICLE INFO

Article history:
Received 18 January 2015
Received in revised form
20 August 2015
Accepted 30 August 2015
Available online 5 September 2015

Keywords:
Life cycle assessment
Building insulation materials
Uncertainty
Propagation

ABSTRACT

Building insulation materials have a significant effect on the reduction of heating/cooling energy consumptions of buildings. From a life cycle perspective, the comparison of different types of insulation materials should consider the building energy consumption together with the environmental emissions during the manufacturing, production, transportation, using and recycling phases of insulation materials. However, this comparison suffers from many sources of uncertainty, especially the parameter identification of insulation materials. In this study, a life cycle inventory analysis model is established and applied to compare the life cycle performance of eight types of insulation materials in an uncertain framework. For each parameter, a probability density function is explicitly specified through a parameter identification process, and the data uncertainty is propagated by Monte-Carlo simulation, the inventory analysis results are transformed from a concrete value into a probability distribution around a mean value, and sensitivity analysis is implemented to identify uncertainty and variability affecting produced the life cycle assessment (LCA). The simulation results revealed that physical parameters have a significant contribution to the uncertainty of the insulation materials, especially for life cycle energy consumption of glass wool, the maximum value may even be quadrupled compares to the minimum value. The decision maker may change the choice of insulation materials when data uncertainty is taken into consideration in LCA.

1. Introduction

Building insulation materials refer to those materials or material composites which have significant resistance to heat flow. Due to their heat resistant properties, building insulation materials have been found that they could be used to improve indoor thermal environment as well as decreasing the building heating/cooling loads. In China, over 50% of energy consumption in buildings is for space heating and cooling, energy consumption for heating in northern areas accounts for about 36% China's total building energy consumption (THUBERC, 2014). Therefore, to promote utilization of insulation materials is of great importance to save energy in building for countries under rapid urbanization such as China. Furthermore, since coal is the primary fossil for heating in China, decreasing the heating energy demand also would result in a great impact reducing air pollution and green gas emissions.

With the implementation of stricter building energy efficiency standards and the increasing indoor environment requirement in winter in southern China, building insulation materials have been paid more and more attention. On average, the consumption of building insulation materials has increased by more than 15% per year from 2003 to 2009. Taking one of the insulation materials-Expanded Polystyrene (EPS) as an example, the consumption of EPS has grown by more than 50% in past10 years (CBMI, 2011).

In China, EPS, Extruded Polystyrene (XPS) and Polystyrene Particles (PP) are the most commonly used building insulation materials. Meanwhile, polyurethane (PU), mineral wool (MW), glass wool (GW), foam glass (FG) and phenol formaldehyde (PF) is also used.

Life Cycle Assessment (LCA) has been found to be a useful tool when comparing various products, and many studies have been done on selecting building insulation materials using LCA concept. Most of the studies focused on determining the optimal insulation thickness of walls or roofs in buildings, by analyzing the effect of the climate parameters (Çomaklı and Yüksel, 2003; Ucar and Balo, 2009), the orientation (Ozel, 2011; Ozel and Pihtili, 2007; Ucar and Balo, 2011), and the fuels (Dombaycı et al., 2006). However, the optimum thickness was determined based on life cycle cost (LCC) analyses method, rather than environmental impact analysis.

* Corresponding author. Tel.: +86 021 65984243; fax: +86 021 65983605.
E-mail address: suxing@tongji.edu.cn (X. Su).

http://dx.doi.org/10.1016/j.jclepro.2015.08.113
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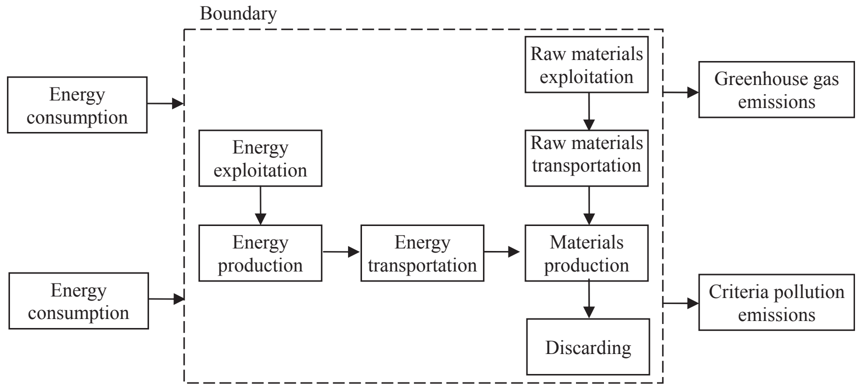

Fig. 1. Boundary of LCA in building insulation materials.

In another words, the optimum thickness is determined from the economic point of view (market demand and price). Among those studies concerning the environmental impact of the insulation materials, most have been conducted to analyze the life cycle energy consumption and environmental emissions of buildings with different insulation materials (Audenaert et al., 2012; Rakhshan et al., 2013; Rodrigues and Freire, 2014; Tettey et al., 2014). Some researchers noted that the usage of building insulation materials could greatly reduce the building energy consumption, and this reduction should be considered when evaluating the life cycle performance of building insulation materials. Nevertheless, this evaluation can't be done without selecting a common functional unit. Anastaselos et al. (2009) discussed an assessment tool, used for evaluating the energetic, economic and environmental performance of thermal insulation solutions, (XPS, EPS and MW). In this study, the materials with a common insulation thickness are compared. In the study by Zabalza et al. (2009), insulation materials with a common mass (kg) are compared, similar with the study by Papadopoulos and Giama (2007). In contrast, some researchers have proposed that the common index should be defined as the mass (kg) needed to cover a 1 m^2 area at a thickness providing an average thermal resistance of 1 m^2 K/W (Schmidt et al., 2004b, a), which is adopted by many researchers (Ardente et al., 2008; Shrestha et al., 2014).

Actually, there are large discrepancies among reported embodied energy values of insulation materials from different studies. Papadopoulos (2005) investigated and reviewed the research status and development trend of commonly used insulation materials in over 10 countries in European, it is concluded that the properties of insulation materials vary significantly. For example, the density of mineral wool varies from 25 to 200 kg/m^3, and the corresponding primary embodied energy varies from 110 to 550 kWh/m^3.

As for any LCA study, results are subject to uncertainty due to the combined effects of data variability; the uncertainty of these parameters contributes directly to the uncertainty of the outcome of the LCA analysis (Bedford and Cooke, 2001; Hofstetter, 1998; Huijbregts, 1998; Owens, 1996; Tukker, 1998), and thus should be explicitly taken into account during the LCA analysis. The stochastic modeling is the most frequently-used method to propagate uncertainties in LCA, which propagates probability distributions using random sampling analysis (Lloyd and Ries, 2007). In this study we made a systematic consideration of parameter uncertainty and variability of all the parameters, the properties (density, thermal conductivity, embodied energy, etc.) of eight building insulation materials were investigated and quantified, the statistical distributions for all parameters were adjusted to propagate the life cycle inventories (LCIs) model in a Monte-Carlo framework. The outcome of this analysis is expected to be more reliable than the one neglect the property uncertainties.

2. Materials and method

2.1. The research objective and functional unit

Eight types of building insulation materials which are widely used in practice were subjected to LCA in this paper, including the EPS, XPS, PP, PU, MW, GW, FG and PF. Similar to the study of the life cycle performance of building materials boundary (Huang, 2003; Su, 2010), the upstream of life cycle of building insulation materials include the life cycle of raw materials and the forming process. The disposal phase can be omitted for the waste of insulation is

Table 1
Materials and energy consumption in 1 kg building insulation materials production stage.

PU	PF	MW	GW
0.713 kg polyol 0.285 kg polyisocyanate 0.417 kWh electricity	0.95 kg formaldehyde 0.152 kg phenol 0.333 kWh electricity	0.014 kg formaldehyde 0.028 kg phenol 0.947 kg limestone 0.316 kg cement 0.04 kg fuel oil 0.246 kg raw coal 0.306 kWh electricity	0.873 kg glass 0.862 kg fuel oil 0.297 kWh electricity
EPS	**XPS**	**FG**	**P P**
1.04 kg polystyrol resin 0.9 kg expansion foam 0.047 kWh electricity	1.02 kg polystyrol resin 0.53 kWh electricity	0.814 kg glass 0.003 kg fuel oil 1.50 kWh electricity	0.961 kg polystyrol resin 0.782 kg expansion foam 0.13 kg fuel oil 0.26 kWh electricity

Table 2
Physical parameter of building insulation materials.

Type	Density(kg/m^3)	Thermal conductivity(W/m·K)
EPS	18–22 (GB50736, 2012); 20 (Anastaselos et al., 2009); 18–50 (Papadopoulos, 2005); 20 (Zabalza et al., 2009)	0.041 (GB50736, 2012); 0.04 (MCRISN, 2005); 0.042 (Wang and Wu, 2008)
XPS	32–38 (Wang and Wu, 2008); 30 (Anastaselos et al., 2009); 20–80 (Papadopoulos, 2005)	0.028 (Pan and Wang, 2006); 0.03 (MCRISN, 2005); 0.029 (Wang and Wu, 2008)
PU	40 (Anastaselos et al., 2009); 36.6–46.1 (Li, 2010); 30–80 (Papadopoulos, 2005); 30 (Zabalza et al., 2009)	0.025 (Wang and Wu, 2008); 0.018–0.023 (Qian and Zhu, 2009); 0.024 (Zhou, 2009); 0.025–0.028 (Li, 2010)
MW	80 (Lu, 1993); 55 (Anastaselos et al., 2009); 30–180 (Papadopoulos, 2005); 50 (Zabalza et al., 2009); 150 (Webpage, 2011)	0.044 (Lu, 1993); 0.04 (Zhu, 2003); 0.041 (Xu, 2010)
PP	8–21 (JG158-2004, 2004)	0.06 (JG158-2004, 2004); 0.059 (Wang and Wu, 2008)
GW	13–100 (Papadopoulos, 2005); 170,95 (Webpage, 2011)	0.0419 (Zhu, 2003); 0.031 (Xu, 2010)
FG	160–180 (Xu, 2010)	0.058, 0.065 (Xu, 2010)
PF	30–100 (Webpage, 2011)	0.02–0.025 (Webpage, 2011)

mostly discarded in the end of life of insulation materials in China. The research boundary is shown in Fig. 1.

The functional unit, used for the life cycle analysis, of the building insulation materials is different from the functional unit of conventional materials. The unit mass is used as a functional unit for conventional materials, and the functional unit will be transferred to unit area by the density when used in the building industry. However, the main target of building insulation material is to increase the building thermal resistance, the amount of thermal insulation necessary to provide thermal resistance R = 1 m^2·K/W should be provided for comparison between different materials. Therefore the functional unit, used for the life cycle analysis, of building insulation material can be expressed as equation (1):

$$\text{F.U.} = A \cdot \lambda \cdot R \cdot \rho \tag{1}$$

Where, A is a unit area (1 m^2); λ is the thermal conductivity of materials (W/m·K); R is a unit thermal resistance (1 m^2·K/W); ρ is the density of materials (kg/m^3).

In the calculation process, the life cycle inventory data per unit mass for different materials should be acquired through investigation firstly, and the thickness of each building insulation materials can be calculated based on a unified thermal resistance. Then the weight of each building insulation materials under the same area (1 m^2) conditions can be calculated by density and thickness. Finally, we can use the data from the life cycle inventory analysis of different material per unit mass to multiply the mass in order to conduct the final comparison.

From the functional unit, the density and thermal conductivity are two very important properties of building insulation materials for LCA study, the variability of this parameters and other database parameters maybe result in the uncertainty of the result, this study attempts to investigate results of the life cycle inventory analysis for different building insulation materials with uncertain data.

2.2. Basic data investigation

2.2.1. Data investigation of insulation materials production process

According to the framework of life cycle assessment, the following data should be collected through investigation: the LCI of raw materials, the consumption of raw materials and all types of energy consumption during the production and processing of building insulation materials. Then all these data should be added into the LCI analysis database to calculate the life cycle inventory of building insulation materials. Using one-shot method for PF production as an example, the main raw materials consumption during the production process is Polyhydroxy Compounds (Polyol) and Polyisocyanate, and the main energy consumption is electricity, and the data of upper stage of Polyol and Polyisocyanate should be also investigated for LCA.

The data of material consumption and the direct energy consumption of building insulation materials during the production process are obtained though investigation or BESLCI program. The BESLCI program developed by Tongji University contains the life cycle inventory database of energy production, transportation, building materials manufacture and some air conditioning systems in China (Huang, 2003), most of the parameters related to energy production and transportation are national averaged data from yearbooks in China, which were updated annually, the direct materials and energy consumption of building materials and products are mainly investigated from manufacture factories in Yangtze River Delta region of China (average value per unit mass by monthly metering data of field investigation), which were updated every two or three years, the unit of data is kg/kg or kWh/kg.

Data collection process of all eight types of insulation materials life cycle inventory should be traced back to raw materials and primary energy consumption. Table 1 shows the total direct energy consumption and materials consumption in production stage of building insulation materials by field investigation.

During the stage of transportation, the building materials are assumed that is manufactured in the locality, the transport distance is assumed 50 km for each material.

Finally, the BESLCI software as mentioned before is used to calculate the life cycle energy consumption and environmental emissions unit mass of building insulation materials. The database of BESLCI offers environmental data for energy, material and transport systems, including their life cycles. The environmental data cover primary energy consumption, air emissions (PM, SO_X, NO_X, CO, NMHC) and greenhouse gases (CH_4, N_2O, CO_2).

2.2.2. Data investigation of the physical parameters of the insulation materials

In the previous section, the life cycle inventory of the building insulation materials is based on the weight as a function unit. However, different building insulation materials have different density and thermal performance. There is no comparability on the basis of quality. According to equation (1), we can also find out that further calculation and transformation needs two more physical

Table 3
Comparison of life cycle primary energy consumption per unit mass among different researches (MJ/kg).

	This study	Reference 1 (Gu et al., 2006)	Reference 2 (Anastaselos et al., 2009)	Reference 3 (Zabalza et al., 2009)
EPS	102.9	117	80.8	105.5
XPS	85.4	–	87.1	–
PU	87.3	74	92.2	103.8
MW	22.2	–	24.6	26.4

Table 4
LCI results of building insulation materials per functional unit.

	PU	PF	MW	GW	EPS	XPS	FG	P P
Primary energy consumption (MJ/F.U.)	81	52	64	90	85	75	208	112
Total emissions (g/F.U.)								
PM	4.29	1.02	10.13	2.93	3.66	3.20	7.36	4.85
SO_X	11.93	5.55	26.78	46.94	12.97	10.85	97.66	14.42
NO_X	8.46	5.42	14.58	34.61	9.56	8.01	72.58	10.70
CO	3.82	2.12	6.33	5.94	3.47	3.03	12.95	4.46
NMHC	0.14	0.11	0.11	0.15	0.14	0.13	0.36	0.19
CH_4	0.15	0.08	0.08	0.06	0.17	0.15	0.20	0.23
N_2O	0.06	0.05	0.05	0.09	0.06	0.05	0.19	0.08
CO_2	5831	3508	5848	8631	6247	5450	19,439	8009

parameters: density and thermal conductivity of the building insulation materials. Subject to the level of technology and many other factors, the parameters of different sources of similar building insulation materials are not identical, and could have huge difference. The exact physical parameters of building insulation materials are obtained based on available literature review, as shown in Table 2.

2.3. Uncertainty analysis method

Parameter uncertainty analysis process was used to describe the variation range and variation characteristics of parameters. The variation range and variation characteristics can be calculated according to the corresponding data set of parameters, and the method of probability analysis. However, the data collection is difficult since at least 15 stable samples are required to determine the probability distribution of a parameter though the general methods of statistical analysis. As a result, the standard deviation and probability distribution function of most parameters cannot be obtained by conventional statistical methods. The parameter comes from a wide range of sources, including field investigation, literature review, similar data substitution and expert judgments.

In this study, physical parameters and data of production process of building insulation materials were mainly adopted from literature review. The thermal conductivity could have correlativity, to certain degree, to density, but the linear correlation between these two parameters can hardly be found through regression, sometimes the thermal conductivity of insulation material increased with its density while in some cases the results are almost opposite that the thermal conductivity decreased with increasing of density according to some literature (Li and Chen, 2005; Mıhlayanlar et al., 2008). And as shown in Table 2, it can be found out that the value of the density of insulation materials vary significantly from different sources, some of these parameters are specified in a range and others are fixed values; the value of thermal conductivity of the same building insulation materials coming from different sources have little difference, the gap between the maximum and minimum is usually less than 20%, therefore, the uncertainty distribution of these two parameters can be set independently.

After consulting with experts on the statistical field, these parameters are assumed to follow triangular distribution for the case of inadequate data and information; the probability distributions of other data in production process are determined by data quality analysis. Once the probability of all the input data selected has been determined, the probability distributions of the output data are propagated with a Monte Carlo simulation, this technique involves the random sampling of each probability distribution within the model to produce at least 10,000 scenarios and a confidence level of 95% in order to have a sufficient high number of trials.

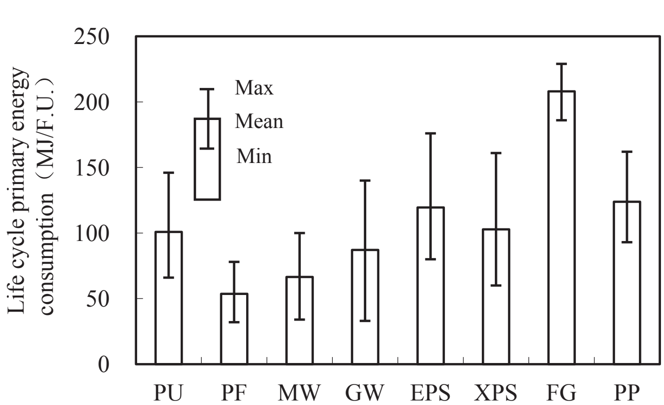

Fig. 2. Life cycle primary energy consumption of building insulation materials under uncertain data.

3. Results and discussion

First, the life cycle inventories for eight building insulation materials based on unit mass are calculated by BESLCI software. The results show that foam glass has the largest life cycle primary energy consumption (158.8 MJ/kg) among all the eight materials, EPS takes second place (102.9 MJ/kg), and the Mineral wool is the least (22.1 MJ/kg). With respect to environmental emissions, PF has the least life cycle air emissions, include PM, SO_X, NO_X and CO. The sorting in the aspect of greenhouse gases emissions is similar to primary energy consumption. The transportation stage account for 3.5–7.1% of all life cycle primary energy consumption (3.5% for PU, 5.1% for PF, 7.1% for MW, 3.8% for GW, 3.3% for EPS, 3.6% for XPS, 5.3% for FG, 3.8% for PP).

In order to test the accuracy of these calculation results, the results are also compared to literature, as shown in Table 3, it can be found that the results of this study are close to the results obtained by other researchers, the maximum relative difference is only 21% for EPS, this difference may be caused by low density of EPS, considering the energy and environmental emissions database of different LCA software may be different, the data in this paper are considered reasonable.

As noted previously, the functional unit of life cycle inventory analysis should be converted into the same thermal conditions for comparison. The calculation results per functional unit are shown in Table 4.

As shown in Table 4, FG has the largest life cycle energy consumption and the largest CO_2 emission, while the PF has the least. There is no significant difference in the life cycle primary energy among three most commonly used building insulation materials, (e.g., PU, EPS and XPS).

The uncertainty of output data in LCI is propagated by Monte-Carlo simulation, the life cycle primary energy consumption of

Table 5
Statistics of Monte Carlo simulation.

	PU	PF	MW	GW	EPS	XPS	FG	PP
Base case	81	52	64	90	85	75	208	112
Mean	101	54	67	88	119	103	208	125
Median	98	53	66	87	112	98	208	123
Coeff. of variability	0.2492	0.2583	0.2977	0.3708	0.2525	0.3086	0.0614	0.1661
Minimum	66	32	34	33	80	60	186	93
Maximum	146	78	100	140	176	161	229	162

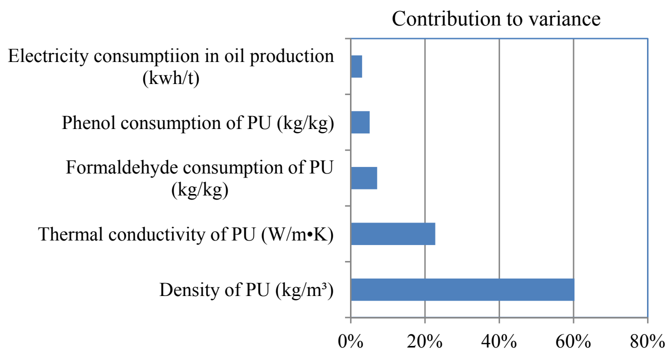

Fig. 3. Sensitivity analysis of life cycle primary energy consumption of PU.

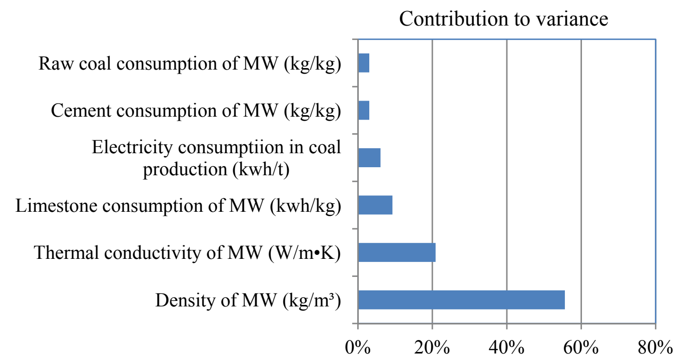

Fig. 5. Sensitivity analysis of life cycle primary energy consumption of MW.

building insulation materials under the uncertain data is presented in Fig. 2 (some details can be found in Table 5), which shows that there is a significant uncertainty in LCI of building insulation materials. Especially for glass wool, the maximum value is over 4 times as the minimum value. The LCI of foam glass has the lowest uncertainty, of which the maximum value is about 1.2 times as the minimum value. Actually, the coefficient of variability of glass wool is up to 37%, it is an unacceptable value for 20% is the upper limit value for acceptable in uncertainty analysis (Su, 2010).

A sensitivity analysis is provided to investigate the sources of uncertainty, as shown in Figs. 3–10 (In these figures, the unit of kgce means kilogram of coal equivalent), uncertainty of the result is mainly due to physical parameters of the insulation materials, thermal conductivity together with density contribute about 47% and 66.9% to the total uncertainty for foam glass and glass wool respectively, then is the raw materials and energy consumption in production stage, and the coal consumption of power generation has also made some contribution to the uncertainty, for coal is the dominant energy and the energy production efficiency increased year by year in China, by the end of 2013, 70% of China's power generation capacity came from thermal power plants (CEPYEC, 2014). An important reason for this big uncertainty could be the application of Monte-Carlo simulation in LCI has its own limitations: probability distribution of many input variable is defined based on hypothesis or empirical information, use triangle distributions for variable of physical parameters may cause an additional source of uncertainty, the CV (coefficient of variability) of density of GW is 34.6% when triangle distributions is assumed, which will be reduced to 10% if normal distribution selected; Second reason is the functional unit selected in this study for comparison convenience, because the density is bring brought in calculation, which increased the uncertainty of input parameters, and the correlations between density and thermal conductivity is ignored for the relationship is nonlinear. Another reason is the data of physical parameters is not corresponding with data of production process, and variability of the input parameters is enlarged which will increase the uncertainty of output.

4. Conclusions

In this paper, a life cycle inventory and a Monte-Carlo based uncertainty analysis were performed on eight building insulation materials. The results show that without taking uncertainty into

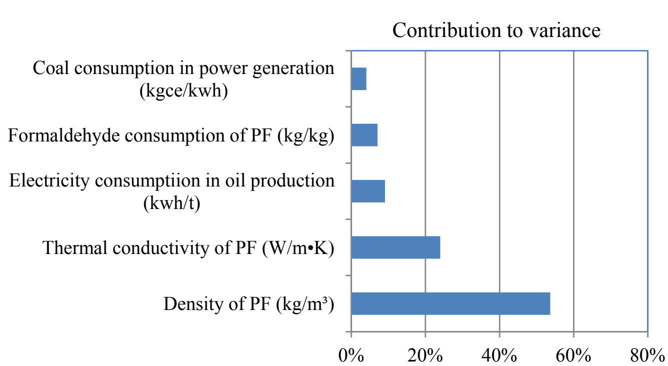

Fig. 4. Sensitivity analysis of life cycle primary energy consumption of PF.

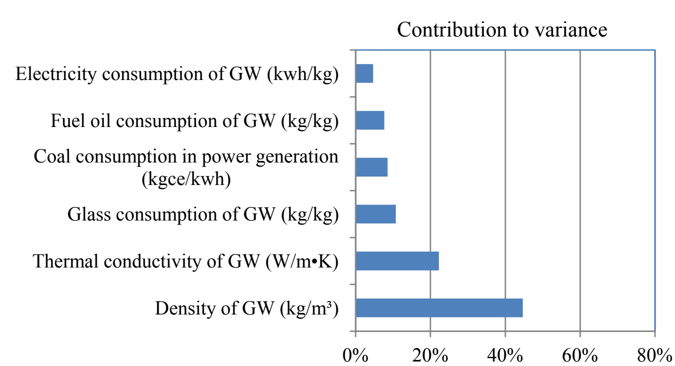

Fig. 6. Sensitivity analysis of life cycle primary energy consumption of GW.

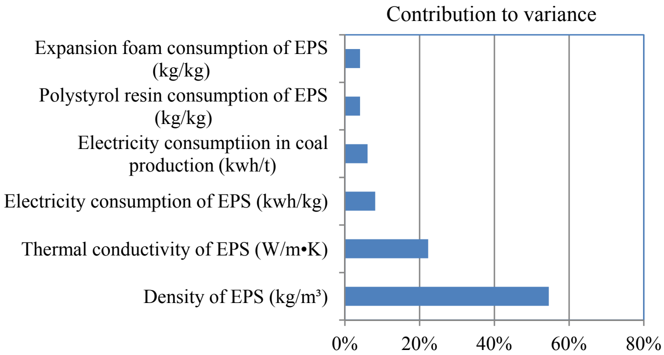

Fig. 7. Sensitivity analysis of life cycle primary energy consumption of EPS.

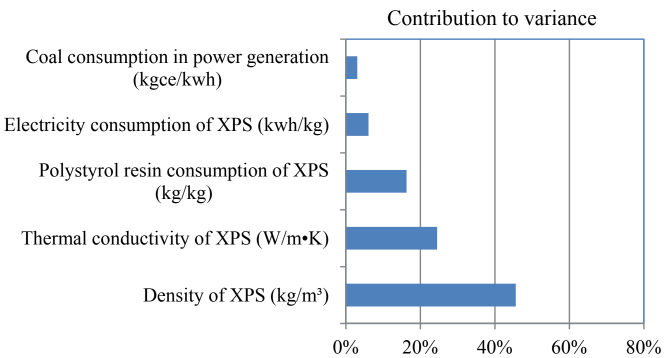

Fig. 8. Sensitivity analysis of life cycle primary energy consumption of XPS.

account, FG has the largest life cycle energy consumption and the largest CO_2 emission, while the PF has the least. There is no significant difference in the life cycle primary energy among three most commonly used building insulation materials (Polyurethane, EPS and XPS). However, when uncertainty is taken into consideration, GW and MW have the largest uncertainty in life cycle primary energy, while the uncertainty of the FG analysis results is relatively small. In most cases, PF is much more environmental friendly than PU, EPS and XPS which consumes the least primary energy. According to sensitivity analysis, the uncertainty and variability of parameters have a significant influence on LCA results. One reason is that the density is assumed as independence to thermal conductivity parameters and the physical parameters are all assumed follow triangular distribution, the physical parameters are not corresponding with materials production data distribution, these factors may all contribute to the uncertainty of results. The second

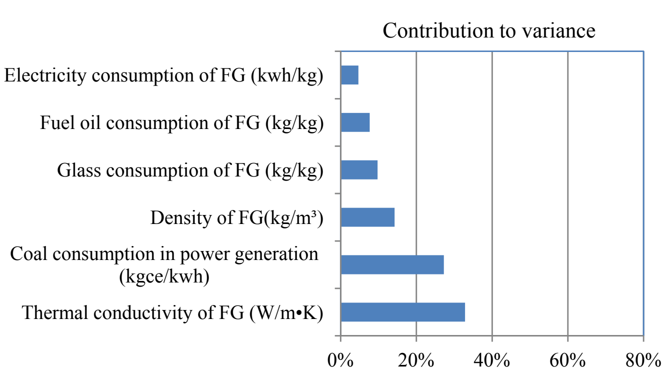

Fig. 9. Sensitivity analysis of life cycle primary energy consumption of FG.

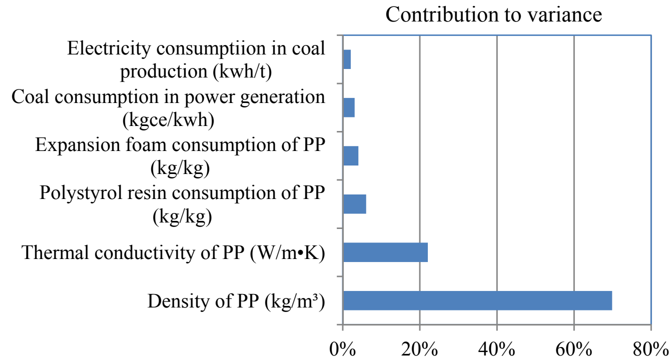

Fig. 10. Sensitivity analysis of life cycle primary energy consumption of PP.

reason is that the energy production efficiency increased annually in China.

This study has shown that there is a significant lack of process data and corresponding physical parameters of insulation materials currently available in China and further improvements in the quantity of this data are needed to increase the reliability of life-cycle inventories. In the future we hope that more studies will be carried out in order to amplify the experience among the LCA practitioners on uncertainty assessment by Monte Carlo simulation. Forthcoming research will focus on best practice on probability distributions for different parameters, technologies, and the methodology of quantifying the uncertainty of nonlinear parameters. It will help avoid the arbitrary assignment of triangular probability distributions in presence of incomplete information and the epistemic uncertainties, and facilitate the use of LCA and increase its consistency from one study to another.

Acknowledgments

This research has been supported by the National Natural Science Foundation of China under Grant No. 51408420, the Action Plan for Young Talents of Tongji University under Grant No. 2014KJ030, and Opening Funds of State Key Laboratory of Building Safety and Built Environment.

References

Anastaselos, D., Giama, E., Papadopoulos, A.M., 2009. An assessment tool for the energy, economic and environmental evaluation of thermal insulation solutions. Energy Build. 41, 1165–1171.
Ardente, F., Beccali, M., Cellura, M., Mistretta, M., 2008. Building energy performance: a LCA case study of kenaf-fibres insulation board. Energy Build. 40, 1–10.
Audenaert, A., De Cleyn, S.H., Buyle, M., 2012. LCA of low-energy flats using the Eco-indicator 99 method: impact of insulation materials. Energy Build. 47, 68–73.
Bedford, T., Cooke, R., 2001. Probabilistic Risk Analysis: Foundations and Methods. Cambridge University Press.
CBMI, 2011. Almanac of China Building Materials Industry.
CEPYEC, 2014. China Electric Power Yearbook 2013. China Electric Power Press.
Çomaklı, K., Yüksel, B., 2003. Optimum insulation thickness of external walls for energy saving. Appl. Therm. Eng. 23, 473–479.
Dombaycı, Ö.A., Gölcü, M., Pancar, Y., 2006. Optimization of insulation thickness for external walls using different energy-sources. Appl. Energy 83, 921–928.
GB50736, 2012. Design Code for Heating Ventilation and Air Conditioning of Civil Buildings in China.
Gu, D., Zhu, Y., Gu, L., 2006. Life cycle assessment for China building environment impacts. J. Tsinghua Univ. (Sci Tech) 46, 1953–1956.
Hofstetter, P., 1998. Perspectives in Life Cycle Impact Assessment: a Structured Approach to Combine Models of the Technosphere, Ecosphere, and Valuesphere. Springer Science & Business Media.
Huang, Z., 2003. The Model and Case of the Life Cycle Assessment of Building Energy System. Tongji University, Shanghai.
Huijbregts, M.J., 1998. Application of uncertainty and variability in LCA. Int. J. LCA 3, 273–280.

JG158-2004, 2004. External Thermal Insulation Rendering Systems Made of Mortar with Mineral Binder and Using Expanded Granule as Aggregate. The Construction Industrial Standard for China.
Li, J., 2010. Twin heat flow meter measurement methods for thermal conductivity of polyurethane thermal insulation materials. Chem. Propellants Polym. Mater. 8, 63–66.
Li, M., Chen, Y., 2005. Relation of density and thermal conductivity of micro-porous calcium silicate insulation material. J. Chin. Ceram. Soc. 33, 1414–1417.
Lloyd, S.M., Ries, R., 2007. Characterizing, propagating, and analyzing uncertainty in life-cycle assessment: a survey of quantitative approaches. J. Ind. Ecol. 11, 161–179.
Lu, Y., 1993. Practical Heating and Air-conditioning Design Handbook. China Construct Industry Press.
MCRISN, 2005. Building Exterior Insulation Technology Guide. The Ministry of Construction Research Institute of Standards and Norms.
Mıhlayanlar, E., Dilmaç, Ş., Güner, A., 2008. Analysis of the effect of production process parameters and density of expanded polystyrene insulation boards on mechanical properties and thermal conductivity. Mater. Des. 29, 344–352.
Owens, J.W., 1996. LCA impact assessment categories. Int. J. LCA 1, 151–158.
Ozel, M., 2011. Effect of wall orientation on the optimum insulation thickness by using a dynamic method. Appl. Energy 88, 2429–2435.
Ozel, M., Pihtili, K., 2007. Optimum location and distribution of insulation layers on building walls with various orientations. Build. Environ. 42, 3051–3059.
Pan, W., Wang, Y., 2006. Technical properties of XPS plate used for outer insulation of external wall and its application. Archit. Technol. 10, 736–739.
Papadopoulos, A.M., 2005. State of the art in thermal insulation materials and aims for future developments. Energy Build. 37, 77–86.
Papadopoulos, A.M., Giama, E., 2007. Environmental performance evaluation of thermal insulation materials and its impact on the building. Build. Environ. 42, 2178–2187.
Qian, B., Zhu, J., 2009. Technology progress of thermal insulation materials of building energy efficiency. Constr. Conserv. Energy 2, 024.
Rakhshan, K., Friess, W.A., Tajerzadeh, S., 2013. Evaluating the sustainability impact of improved building insulation: a case study in the Dubai residential built environment. Build. Environ. 67, 105–110.
Rodrigues, C., Freire, F., 2014. Integrated life-cycle assessment and thermal dynamic simulation of alternative scenarios for the roof retrofit of a house. Build. Environ. 81, 204–215.
Schmidt, A., Jensen, A., Clausen, A., Kamstrup, O., Postlethwaite, D., 2004a. A comparative life cycle assessment of building insulation products made of stone wool, paper wool and flax. Int. J. LCA 9, 122–129.
Schmidt, A., Jensen, A., Clausen, A., Kamstrup, O., Postlethwaite, D., 2004b. A comparative life cycle assessment of building insulation products made of stone wool, paper wool and flax. Int. J. LCA 9, 53–66.
Shrestha, S.S., Biswas, K., Desjarlais, A.O., 2014. A protocol for lifetime energy and environmental impact assessment of building insulation materials. Environ. Impact Assess. Rev. 46, 25–31.
Su, X., 2010. Validity Analysis of Building Life Cycle Inventory. Tongji University.
Tettey, U.Y.A., Dodoo, A., Gustavsson, L., 2014. Effects of different insulation materials on primary energy and CO_2 emission of a multi-storey residential building. Energy Build. 82, 369–377.
THUBERC, 2014. 2014 Annual Report on China Building Energy Efficiency.
Tukker, A., 1998. Uncertainty in life cycle impact assessment of toxic releases practical experiences-arguments for a reductionalistic approach? Int. J. LCA 3, 246–258.
Ucar, A., Balo, F., 2009. Effect of fuel type on the optimum thickness of selected insulation materials for the four different climatic regions of Turkey. Appl. Energy 86, 730–736.
Ucar, A., Balo, F., 2011. Determination of environmental impact and optimum thickness of insulation for building walls. Environ. Prog. Sustain. Energy 30, 113–122.
Wang, H., Wu, W., 2008. Optimizing insulation thickness of external walls for residential buildings. J. Chongqing Univ. 31, 937–941.
Webpage, 2011. http://www.shengquanchem.com/product.asp?keyno=128.
Xu, C., 2010. The problems and solutions of non combustible thermal insulation material in EIFS. Wall Mater. Innov. Energy Sav. Build. 2, 38–41.
Zabalza, I., Aranda, A., Scarpellini, S., Díaz, S., 2009. Life cycle assessment in building sector: state of the art and assessment of environmental impact for building materials. In: 1st International Exergy, Life Cycle Assessment, and Sustainability Workshop & Symposium (ELCAS), pp. 4–6.
Zhou, H., 2009. Insulation and energy-saving for exterior wall of building. Constr. Energy Conserv. 38, 16–18.
Zhu, Y., 2003. Application of Thermal Insulation Material in Building Energy Saving. Chinese Building Materials Industry Press.