ENVIRONMENTAL ASSESSMENT OF ENERGY EFFICIENCY IMPROVEMENTS IN HISTORIC BUILDINGS: SOLID WALL INSULATION

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Abstract. Since the elaboration of the Leipzig Charter on Sustainable European Cities in 2007, energy retrofit has become one of the priorities for the European Union. However, to achieve a sustainable development of the built environment, we need to not only address the energy consumption in the operational phase but also the environmental aspects associated with the production of the materials applied in the energy retrofit measures. In this case the sustainability is evaluated by comparing the embodied impacts generated during the entire life cycle of the materials with the energy use reduction achieved due to the thermal performance improvement.
Keywords: Traditional buildings, Energy efficiency, Solid wall insulation, Life cycle assessment, Thermal simulation

1. Introduction

This research focuses on the environmental assessment of energy retrofit measures applied in historic buildings. Within the total Scottish building stock, historic and traditionally constructed buildings represent the large proportion of 19% (Curtis 2010), and considering the low rate of renovation in the European countries (between 1.2% and 1.4% per year (Dyrbøl, Thomsen, et al. 2010)) these building are going to play a crucial role in the future development of sustainable cities.

Any retrofit work has an associated environmental load, from the extraction of raw materials to the disposal and recycling of manufactured products. In order to evaluate the final result of the refurbishment, a global assessment of the different phases involved in the process is necessary.

2. Methodology

Combined use of Life Cycle Assessment and thermal simulation software facilitates the calculation of environmental impacts associated with the production of the insulation and the impacts avoided during the operational phase. Following, the main steps of the methodology are briefly explained:

i. *Case study characterization*. First, the case study used in this research was analysed. Building geometry, physical characteristics and monitored data from before and after the insulation were used to achieve an accurate simulation of the thermal performance.
ii. *Insulation techniques appraisal*. The case study was insulated by injecting polyurethane foam. For a more comprehensive evaluation, the most common retrofit measures were investigated and analysed. Information related to the environmental impacts was collected for every product used in the different retrofit options studied.
iii. *Thermal simulation*. Numerical simulation was used to estimate the energy demand for space heating before and after the application of the different insulation techniques.
iv. *Environmental assessment*. Lastly, the assessment of the saved energy and environmental impacts was conducted using the simulation results and the information gathered from environmental products declarations.

3. Bogendollo – A 18th century case study

The model used in this paper for the simulation and environmental assessment is based on a previous research project where an innovative insulation method was successfully applied in a historic listed building in Aberdeenshire (Abdel-Wahab and Bennadji 2012). This experiment was conducted with a particular emphasis on maintaining all the original architectural features and causing no harm to the building's fabric while improving the thermal performance of the envelope. The trial was funded by the Scottish Government and the European Regional Development Fund.

4. Internal insulation

Following, the insulation technologies included in this research are described. All these options are summarised in Table 1 including materials employed, thicknesses and estimated U-value. The calculated U-value of the original wall before the improvement was 1.016 W/m^2K.

TABLE 1. Insulation measures analysed.

	Polyurethane foam		Phenolic board		Wood	Calc-Silc
	PUR1	PUR2	PHB1	PHB2	WFB	CSB
Layer 1	**PUFoam**[1] 65 mm	**PUFoam**[2] 65 mm	Air gap 40 mm	**Phenolic** 40 mm	Air gap 40 mm	Mortar[3] 10 mm
Layer 2	--- ---	--- ---	Battens[4] 0.002 m^3	Cem-brd 12.5 mm	Battens 0.002 m^3	**Calc-Sl**[5] 50 mm
Layer 3	--- ---	--- ---	**Phenolic**[6] 60 mm	Render 3 mm	**WoodFb**[7] 60 mm	F. Mesh 0,155 kg
Layer 4	--- ---	--- ---	Cem-brd[8] 12.5 mm	--- ---	Fastener 10 units	Render 4 mm
Layer 5	--- ---	--- ---	Fastener[9] 10 units	--- ---	F. Mesh[10] 0,155 kg	--- ---
Layer 6	--- ---	--- ---	Render[11] 3 mm	--- ---	Render 3 mm	--- ---
U-Value	**0.413** W/m^2K	**0.307** W/m^2K	**0.252** W/m^2K	**0.340** W/m^2K	**0.414** W/m^2K	**0.652** W/m^2K

4.1. POLYURETHANE FOAM

Insulation of the cavity existing between the masonry and the lath and plaster (fig. 1) offers a compromised solution in buildings that are often considered as “hard to treat”. Application of foams in the cavity minimises the disruption for the tenants, loss of usable space and the amount of waste produced.

- Open cell (PUR1). In the case study, the insulation material applied was water based foam, which expands slowly with no harmful agents released in the process. The foam allows the wall to breathe thereby controlling moisture movement. In this trial the foam was injected from the attic using fibre tubes inserted in each bay until it reached the top of the wall where it can be visible from the attic.
- Closed cell (PUR2). The available information regarding the environmental impact of open cell PUR foam material is very limited (SPFA 2012) so the study is completed with the analysis of closed cell polyurethane foam. No record of application of this foam has been found, but the installation process is assumed to be the same.

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[1] Spray Polyurethane Foam Association 2012

[2-11] Institut Bauen und Umwelt. Declaration numbers: (2) EPD-PUE-20140017-CBE1-EN; (3) EPD-DAW-2009111-D; (4) EPD-SHL-20120017-IBG1-E; (5) EPD-CSP-2013111-D; (6) EPD-KSI-20130228-IAC1-EN; (7) EPD-GTX-2011111-E; (8) EPD-USG-20130023-IAA1-EN; (9) EPD-EJT-2010211-D; (10) EPD-VIT-2010311-D; (11) EPD-STO-2008211-E

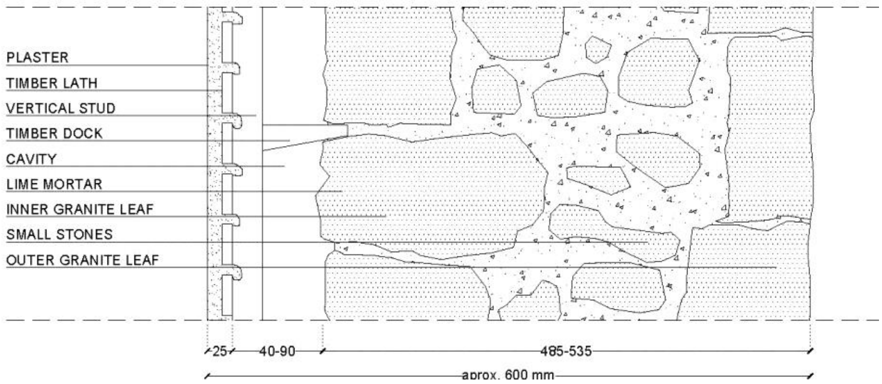

Figure 1. Solid wall section detail (Adapted from Buda, Taylor and Bennadji 2013).

4.2. PHENOLIC BOARD

Phenolic board is one of the most common forms of insulation in traditional buildings despite the harm that this option produce to the original features and the amount of waste and disruption associated to it.

- New dry-lining (PHB1). Two possible applications of this material are included in this paper. The first one will involve the substitution of the existing lath and plaster for a completely new dry-lining including the phenolic board.
- Over the existing dry-lining (PHB2). As an alternative method, this paper also studies the application of the insulation on top of the existing internal finish (Bros-Williamson 2012). This option reduces the amount of material required and the waste produced, but the thickness of the insulation boards is limited due to the loss of internal space.

4.3. WOOD FIBRE BOARD (WFB)

A second method of new internal dry-lining is analysed. This method has been successfully applied by Historic Scotland (Jenkins 2012) in previous research and it is analogous to the one described previously, but in this case the phenolic boards are replaced with wood fibre boards.

4.4. CALCIUM SILICATE BOARDS (CSB)

The last option considered in this paper involves the application of calcium silicate boards on top of the existing masonry wall (Jenkins 2012). This measure requires the elimination of the existing internal dry lining and replacement of the original features (cornicing, skirting, etc.).

5. Thermal simulation

Previous research has shown the importance of the operational phase in the final result of the environmental assessment (Herrera and Bedoya 2012) and the difficulty for modelling the performance of traditional materials (Ingram, Banfill and Kennedy 2011). For an accurate evaluation of the energy efficiency improvement, data collected from in-situ measurements before and after the spray foam application in the case study was used to calibrate the thermal simulation model (fig. 2).

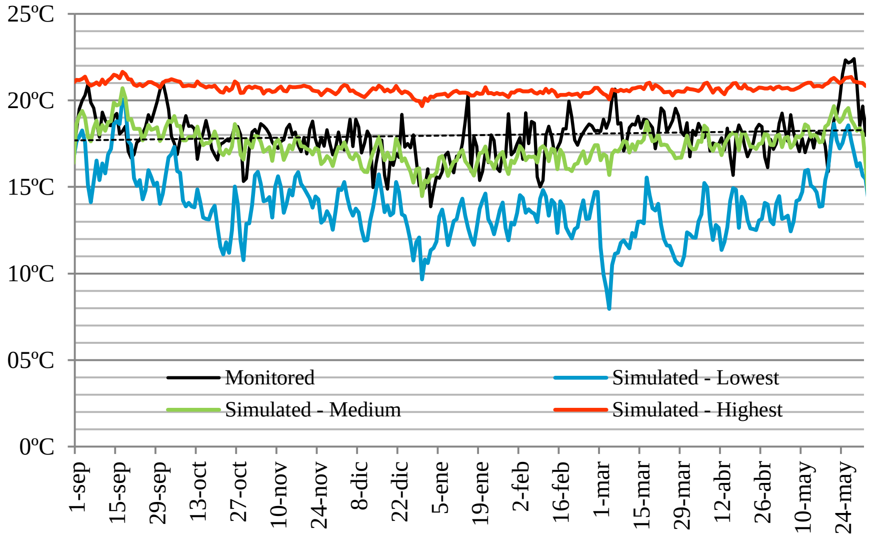

Figure 2. Monitored and simulated internal temperatures.

Three different scenarios of user behaviour have been simulated using EnergyPlus software. The "Medium" scenario set the temperature in 20°C and the heating is on for 74 hours a week from September to May (06:00-09:00; 17:00-24:00 weekdays & 07:00-11:00; 16:00-21:00 weekends). This intermediate scenario obtained very similar results to the actual temperatures recorded in the case study and therefore it will be the one used for all the calculations in this paper. Table 2 shows the results for space heating energy demand in this described scenario with the different insulation techniques.

TABLE 2. Space heating energy demand before and after the insulation.

		PUR 1	PUR 2	PHB 1	PHB 2	WFB	CSB
Pre-Retrofit	[kWh]			27478.5			
Post-Retrofit	[kWh]	20760.2	19633.9	18738.7	19667.2	20242.0	22685.6
Saving	[%]	**24.45**	**28.55**	**31.81**	**28.43**	**26.33**	**19.38**

6. Life cycle assessment

This paper analyses five different environmental impacts related to air and water pollution: global warming (GWP; measured in kg of CO_2-eq), ozone depletion (ODP; kg CFC11-eq), acidification (AP; kg SO_2-eq), eutrophication (EP; kg $(PO_4)^{3-}$-eq) and photochemical ozone creation potential (POCP; kg ethen-eq). For all the insulation technologies studied, information regarding the environmental impacts associated to the production of the materials was collected using Environmental Product Declarations (EPDs). These Type III declarations are voluntary programs that provide quantified environmental data of a product, under pre-set categories of parameters set by a qualified third party and based on life cycle assessment, and verified by that or another qualified third party (GEN 2004).

TABLE 3. Environmental impacts for Option 6 (Calcium Silicate boards).

Environmental impact							
Functional unit		**GWP**	**ODP**	**AP**	**EP**	**POCP**	**Energy**
Adhesive mortar	kg	3.41E-1	1.07E-8	6.46E-4	1.24E-4	9.08E-5	8.20E+0
	m^2	1.36E+0	4.30E-8	2.58E-3	4.97E-4	3.63E-4	1.68E+1
Calc-Silicate boards	t	2.04E+3	4.56E-6	2.15E+0	3.37E-1	2.22E-1	2.82E+4
	m^2	2.04E+1	5.48E-8	2.58E-2	4.04E-3	2.66E-3	3.38E+2
Reinforcement mesh	kg	3.83E+0	2.30E-7	1.45E-2	1.18E-3	2.38E-3	7.55E+1
	m^2	5.94E-1	3.57E-8	2.25E-3	1.83E-4	3.69E-4	1.17E+1
Final coat	m^2	6.60E-1	2.26E-8	5.70E-3	1.89E-4	1.83E-4	8.64E+0
Total/m^2	m^2	**2.30E+1**	**1.56E-7**	**3.63E-2**	**4.91E-3**	**3.57E-3**	**3.75E+2**
Total (333.35 m^2)		**7.67E+3**	**5.20E-5**	**1.21E+1**	**1.64E+0**	**1.19E+0**	**1.25E+5**

This paper considers the impacts associated to the phases of raw material extraction, transport to factory, production and packaging (production and disposal). The rest of the phases (transport to site, installation, end of life, etc.) were not included due to the lack of comparable data for all the products. Table 3 shows an example of a summary for the environmental impacts associated to the production of all the elements needed for the application of calcium silicate boards as internal insulation.

The EPD of polyurethane foam (open cell) uses different units for the acidification (kg H^+ moles-eq), eutrophication (kg N-eq) and photochemical ozone creation (kg O_3-eq) categories. As a result, these impacts are not comparable to those from the rest of the products.

6.1. USE PHASE - ENERGY SOURCES

The environmental assessment will establish the energy and impacts saved with the reduction in the space heating demand after the insulation of the wall. Therefore, it is essential to establish the environmental loads associated to the heat production. Table 4 shows the impacts due to the production of 1 kWh of heat using natural gas (Emmenegger, Heck and Jungbluth 2007), since it is the most common energy source for heating systems in Scotland.

TABLE 4. Energy source impacts and weightings used to calculate UK Ecopoints.

	Energy Sources	Normalization factors		
Impact category	Natural gas	Normalization	Weight	Score
Global warming	2.72E-01	12,269.00	35	0.0029
Ozone depletion	3.58E-08	0.30	8	26.67
Acidification	2.51E-04	58.90	5	0.0849
Eutrophication	2.51E-05	8.00	4	0.50
Photochemical oxidation	6.30E-05	32.20	3.5	0.12

6.2. NORMALIZATION OF RESULTS

For the normalization and weighting of the different categories, this paper uses the “Ecopoints” system developed by the Building Research Establishment (BRE) in 1999 (Dickie and Howard 2000) (Table 4). Normalization is an optional step that allows the calculation of the magnitude of the category indicator results relative to reference information (a given community, person or other system or period of time) (EN ISO 14044). In this case normalization factors are calculated per UK citizen.

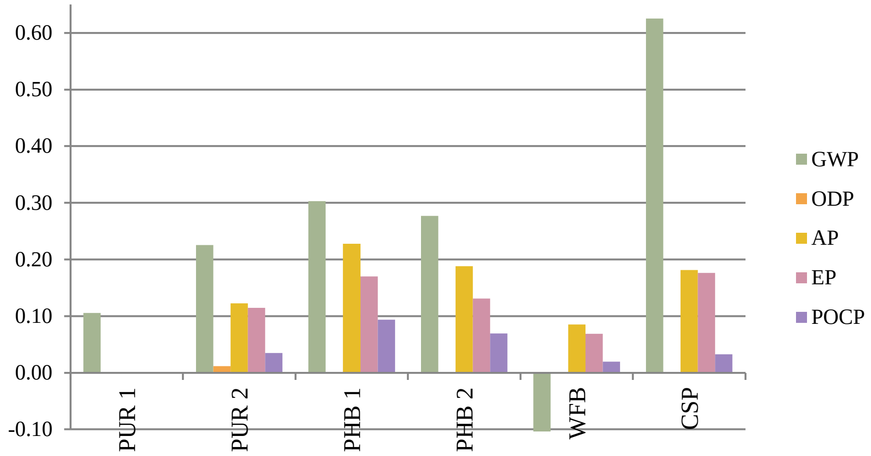

Figure 3. Normalised results of environmental impacts.

Normalised results show the great disparity existing between different retrofit solutions (fig. 3). While Global Warming Potential is the highest impact in 5 of the 6 analysed solutions, insulation with Wood fibre boards presents a negative result in this category due to due carbon sequestrated during the wood growth. Ozone depletion potential is very low in all the analysed solutions with the exception of the “closed cell PUR foam” that contains HFC (5%) on its formulation. Potential of acidification and formation of tropospheric ozone photochemical oxidants is higher in the solutions using phenolic boards because both the insulation panels and the cement plaster boards present high values of SO2-eq. Eutrophication potential is similar in all the proposed solution and only Open cell PUR foam and Wood fibre insulation achieve lower levels of $(PO_4)^{3-}$eq.

7. Discussion of results

Weighting of results is sometimes a controversial step because it implies the assumption of some subjective factors based on monetary values, policy targets or expert panels to define the relative importance of each impact (Peuportier, B. et al. 2011). In this case, use of BRE’s Ecopoint system allows the aggregation of impacts and comparison of different solutions more easily (fig. 4).

Use of wood fibre boards achieves a negative impact after the weighting of the different categories while the solution with calcium silicate boards obtains the worst result in terms of total environmental impact due to the high levels of CO_2-eq associated to its production. Open cell PUR foam (the solution employed in the original case study) cannot be fully evaluated since the units used en 3 of the impacts categories assessed are different and therefore normalization of results were not possible to obtain. The other 3 options achieve similar results. The solution PHB1 obtains bigger impacts due to the greater amount of materials needed for its application.

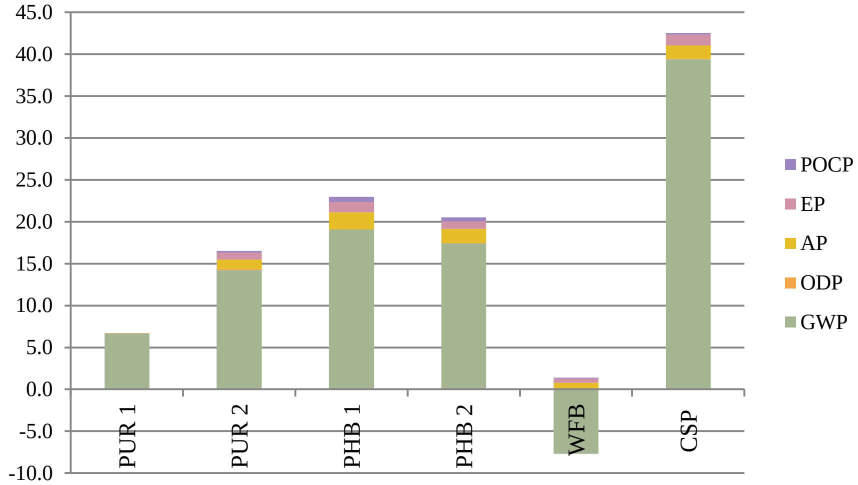

Figure 4. Weighted results of environmental impact.

Table 6 shows the impacts emitted for each solution and the savings achieved with the reduction in the space heating demand assuming the use of natural gas in a heating system with an efficiency of 90%. With the impacts and savings known, it is possible to calculate the "payback" for each category, i.e. the time necessary to achieve an environmental saving similar to the impact produced during the fabrication of the new products.

TABLE 6. Environmental impacts Emitted and Saved (in ecopoints) and Payback (in years).

		PUR 1	PUR 2	PHB 1	PHB 2	WFB	CSP
GWP	E	1.30E+3	2.77E+3	3.71E+3	3.39E+3	-1.50E+3	7.67E+3
	S	2.26E+3	2.63E+3	2.93E+0	2.62E+3	2.43E+3	1.61E+3
	P	**0.57**	**1.05**	**1.27**	**1.29**	**-0.62**	**4.77**
ODP	E	3.56E-5	3.52E-3	2.88E-5	1.19E-5	6.70E-5	5.20E-5
	S	2.97E-4	3.47E-4	3.86E-4	3.45E-4	3.20E-4	2.12E-4
	P	**0.12**	**10.14**	**0.07**	**0.03**	**0.21**	**0.25**
AP	E	2.14E+2	7.20E+0	1.34E+1	1.11E+1	5.02E+0	1.21E+1
	S	2.26E+3	2.43E+0	2.71E+0	2.42E+0	2.24E+0	1.49E+0
	P		**2.96**	**4.95**	**4.58**	**2.24**	**8.15**
EP	E	2.34E-1	9.15E-1	1.36E+0	1.05E+0	5.49E-1	1.64E+0
	S	2.08E-1	2.43E-1	2.71E-1	2.42E-1	2.24E-1	1.49E-1
	P		**3.76**	**5.02**	**4.33**	**2.45**	**11.01**
POCP	E	5.08E+1	1.11E+0	3.02E+0	2.23E+0	6.31E-1	1.19E+0
	S	5.23E-1	6.10E-1	6.80E-1	6.08E-1	5.63E-1	3.73E-1
	P		**1.82**	**4.44**	**3.67**	**1.12**	**3.20**
ENERGY	E	7.57E+3	1.84E+4	2.45E+4	1.60E+4	1.82E+4	3.47E+4
	S	8.29E+3	9.68E+3	1.08E+4	9.64E+3	8.93E+3	5.92E+3
	P	**0.91**	**1.90**	**2.27**	**1.66**	**2.04**	**5.87**

8. Conclusions

Within the limitations of this paper it is necessary to highlight those associated to the boundary chosen for the assessment. This paper does not take into account the environmental impacts due with the transport to the site or the installation works. Even if most of the EPDs used in this paper correspond to products from continental Europe, all the solutions analysed can be applied using products manufactured in the United Kingdom and therefore the environmental impact due to the transport would be similar.

Replacement of existing features (original lath and plaster, cornicing, skirting, etc.) is not taken into account in this paper either. These changes might be even more important from an historic and aesthetical point of view as their final influence on the environmental assessment is limited. Insulation of the cavity existing between the masonry and the internal dry-lining might offer a compromised solution between efficiency, conservation and cost-effectiveness. Further research on different materials for cavity insulation (cellulose, polystyrene beam, mineral wool) is therefore needed.

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References

ABDEL-WAHAB, M. and BENNADJI, A., 2013. Skills development for retrofitting a historic listed building in Scotland. *International Journal of Low-Carbon Technologies.*

BROS-WILLIAMSON, J. 2012. Thermal and condensation analysis of a typical solid wall following a refurbishment intervention. *CIC Start Online Feasibility Study FS58 and Webinar 3*

BUDA, G., TAYLOR, B. and BENNADJI, A., 2013. The nature of mass masonry granite walling and the potential for retrofit internal wall insulation strategies. *Journal of Building Survey, Appraisal & Valuation,* 2(1), pp. 36-43

BUILDING RESEARCH ENERGY CONSERVATION SUPPORT UNIT (BRECSU) http://www.boilers.org.uk/

CURTIS, R., 2010. Climate Change and Traditional Buildings: The Approach Taken by Historic Scotland. *Journal of Architectural Conservation,* 16(3), pp. 7

DICKIE, I. and HOWARD, N., 2000. Assessing environmental impacts of construction: Industry consensus, BREEAM and UK Ecopoints. Building Research Establishment UK.

DYRBØL, S., THOMSEN, K.E. and ALBÆK, T., 2010. European Directive on the Energy Performance of Buildings-Energy policies in Europe-Examples of best practices. *2010 ACEEE Summer Study on Energy Efficiency in Buildings*. August 2010. pp. 126-140

EMMENEGGER, M., HECK, T. AND JUNGBLUTH, N. 2007. Natural gas. Life cycle inventory of energy systems *Report Ecoinvent Data v2.0 nº5.* Swiss Center for Life Cycle Inventories, Dübendorf, CH.

GLOBAL ECOLABELING NETWORK, 2004. Information paper: Introduction to Ecolabelling. *GEN, Ottawa, July*.

HERRERA, D. AND BEDOYA, C., Evaluación de la rehabilitación térmica de fachadas en términos de sostenibilidad. In: *4º Congreso de patología y rehabilitación de edificios, PATORREB,* Santiago de Compostela, Spain, 2012.

INGRAM, V., BANFILL, P. and KENNEDY, C., 2011. Towards an objective assessment of energy efficiency in heritage buildings. *World Renewable Energy Congress, Linköping, Sweden.*

JENKINS, M., 2012. Historic Scotland Refurbishment Case Study 6. [Online] Available from: http://www.historic-scotland.gov.uk/refurb-case-study-6.pdf [Accessed 13/03/2014]

PEUPORTIER, B., et al. 2011. Life cycle assessment methodologies in the construction sector: the contribution of the European LORE-LCA project. In: *Sustainable Building Conference, Helsinki.*

SPRAY POLYURETHANE FOAM ALLIANCE (SPFA,) 2012. Life Cycle Assessment of Spray Polyurethane Foam Insulation for Residential & Commercial Building Application. [Online] Available from: https://www.certainteed.com/resources/SPFALCALongSummary.pdf [Accessed 25/04/2014]