An Assessment of Differing Environmental and Economic Factors and their Impact on the Development of a Circular Economy for Refrigerated Display Cabinets in the UK

Deborah Andrews

Senior Lecturer

School of Engineering, London South Bank University

103 Borough Road, London SE1 0AA, UK

Zaneta Muranko

Research Student

School of Engineering, London South Bank University

Issa Chaer

Reader

School of the Built Environment and Architecture, London South Bank University

Introduction

A number of environmental, social and economic factors clearly show that the Linear Economy (in which products are manufactured, used and treated as waste at end-of-life) is unsustainable and as a consequence an alternative model – the Circular Economy – is being advocated. This model mirrors natural systems and at end-of-life products and their constituent elements are no longer disposed of as waste but are recycled to become technical and natural 'nutrients' for the next generation of products. Prior to this, products, components and materials should also be retained in the economy through repair, reuse and remanufacture until they can no longer be used.

By definition the development of a Circular Economy must include economic as well as environmental factors; however the optimum environmental choice is not always the optimum economic choice, which further complicates the development of this new business model. This paper presents a specific case study in the commercial refrigeration industry and considers the environmental and economic implications that affect the potential substitution of insulation materials for Refrigerated Display Cabinets (RDCs). The case study also illustrates the complexity of decision making towards the development of a Circular Economy.

Context – Refrigerated Display Cabinets

Refrigerated display cabinets (RDCs) are a key part of the cold chain which ensures the safe and hygienic supply of food from 'farm to fork'. They evolved in conjunction with self-service food stores throughout the 1950s and '60s and there are now 800,000 RDCs in the 9,200+ supermarkets in the UK alone (Bibalou et al, 2011). RDCs were developed to keep perishable food at the optimum temperature which ranges from 4^{o}C (for dairy, meat, fish and poultry), and 5^{o}C (for ready meals) to 8^{o}C (for vegetables). In addition to keeping food on the store floor they are important merchandising units which encourage customers to buy products. Keeping food cold is not difficult or particularly energy intensive providing that it is kept in a well-insulated box; because RDCs are used for merchandising however the majority are open fronted which allows warm ambient air into the display area and cool air to 'escape' into the store, and consequently energy consumption increases as the refrigeration systems work to maintain temperature. Air curtains are most commonly used to control this air flow although plastic curtains and glass doors reduce operational energy consumption more than air curtains (particularly in warmer climates). They can adversely affect the sale of non-uniform products (which customers like to examine prior to selection) however and consequently they are not widely used in the UK (Evans, 2014).

At present in the UK alone 5,800 GWh electricity is used annually by supermarkets to operate refrigeration units (Carbon Trust, 2011) and refrigeration activities associated with supermarkets produce 1.5 M tCO_{2e} (Maidment et al, 2010). Consequently there has been a drive to reduce operational energy consumption and greenhouse gas emissions from RDCs by developing more efficient refrigeration systems and components, using new and alternative refrigerants and by reducing refrigerant leakage.

The average weight of a RDC is about 0.5 tonnes which means that 400,000 tonnes materials are currently utilised in this part of the cold chain. Product life varies according to the type of materials used (e.g. stainless steel does not rust like other steels) as a result of which some units are scrapped after 3 to 5 years; furthermore many units are also removed from stores as part of refit projects before they reach end-of-life, which could be as long as 20 years providing that the RDCs are properly maintained. Product life can also be extended through remanufacture: this process could be relatively cosmetic (e.g. repainting and replacement of minor parts) and/or more extensive through reengineering and upgrading (e.g. replacing old components with new more efficient models). Although this process is both economically and environmentally beneficial the rate of remanufacture for RDCs is relatively low at about 12.5% (Bibalou et al, 2012); this is due to a number of factors including concern about warranty and the misconception that 'second-hand can't be as good as new' (APSRG, 2014).

Table 1: Materials in a typical RDC

Materials in a typical RDC	
Metals	steel (stainless, carbon, galvanised), aluminium alloy, brass, copper
Polymers	polyurethane, polystyrene & phenolic foams, polycarbonate, polypropylene, polyethylene
Glass	plate, fibre
MDF	wood and other natural fibres, urea formaldehyde resin
Electronics	including precious metals

The best quality RDCs are already efficiently designed, engineered and constructed, and typically include the materials shown in Table 1. They also include a significant number of mechanical fixings, which facilitate disassembly. In conjunction with the types of materials used these processes mean that complete cabinets and individual components can be remanufactured and/or reused; similarly at end-of-life the majority of the cabinets (by mass) are recycled. These practices mean that there is already a partial Circular Economy in the RDC sector, which is supported by British manufacturers such as The Bond Group.

Recycling is of course in part dependent on an infrastructure and a market for recyclates, both of which are well established in the case of metals and glass; as yet however this is not the case for electronics (although recovery rates for WEEE are gradually increasing (BIS, 2015)) or PUR (rigidised polyurethane foam) insulation. Polyurethane foam insulation is totally synthetic and was developed in the 1960s by NASA for use in the space programme. It is made reacting polymeric polyols with isocyanates and then using a blowing agent to expand the foam to form sheets, fill cavities and/or moulds and it has a comparably low mass and thermal conductivity. These properties made it an excellent choice for commercial and domestic fridge insulation in many respects and manufacturing processes were developed to capitalise on this material's properties. Blowing agents used to be CFC or HCFC-based (and therefore to contribute to ozone depletion and global warming) although it is now possible to get CFC and HCFC-free agents derived from natural vegetable sources. Although PUR can be recycled it is a thermoset polymer which means that it cannot be recycled like thermoplastics (i.e.by re-melting and re-moulding); it can be recycled chemically or by pyrolysis (and split for reprocessing into new polyurethanes) or recycled mechanically (and ground into filler etc.). Polyurethanes are adhesive and consequently the insulation bonds to the steel panels during the blowing process. This is advantageous because it increases structural integrity but it also makes disassembly difficult and the PUR fragments as it is scraped off the inside of the panels. This is time consuming and does not facilitate reuse, as a result of which RDC insulation is usually either smelted during the steel recycling process or incinerated for energy from waste.

As part of the challenge to develop a complete Circular Economy for this industrial sector this paper now discusses the potential substitution of PUR with other insulation materials; materials performance, overall environmental impact, and related economics are considered in order to ascertain whether use of an alternative insulation materials is viable and appropriate or whether other manufacturing solutions and/or business models should be considered.

Methodology

The study is based on the insulation in the rear panel from a typical RDC manufactured by The Bond Group (see figure 1); the insulation is 3.42m^2 and 40mm thick and is encased in painted steel.

Seven insulation materials were considered as substitutes:

- 2 x established synthetic materials: fibre glass, mineral wool
- 2 x new synthetic materials:
    - Aerogel (comprised of silica based materials, graphite and PE)
    - VIPs (Vacuum Insulated Panels comprised of a metallised plastic film envelope (made from Al, PET, PP and HDPE) and a silica-based core).
- 3 x natural materials: cork, sheep's wool and cotton (which is made from recycled material)

These materials all have differing thermal properties which affect operational energy consumption so the environmental impact of energy consumption is combined with that of the insulation. Technical data is taken from a previous case study (Foster et al, 2013). Thicker and thinner insulation could be used to create panels with the same level of thermal conductivity as the 40mm PUR but it is unlikely that this model will be adopted by industry because thicker panels will either increase the external dimensions of the cabinets (and compromise RDC modularity) or reduce internal volume (and thus display area) while thinner panels will compromise structural integrity; consequently all calculations are based on 40mm thick material.

In addition to thermal conductivity materials' properties such as resistance to humidity, compaction and fungal growth also differ and functional life of the insulation varies from 15 – 100 years. Similarly durability varies; for example VIPs (Vacuum Insulated Panels) are less robust than other materials and although their functional life is 20 years, if they are damaged the vacuum is destroyed and functional life ends prematurely. Typical RDC life is about 5 years before it is replaced (during store refurbishment for example) or remanufactured (as described above) and the combined life cycle impacts of operational energy use and product are modelled over this time period.

Figure 1: ‘Chicago’ Refrigerated Display Cabinet © The Bond Group

Life Cycle Assessment

The product life cycles include extraction of raw materials, bulk processing, manufacture, use (operational energy), and treatment at end-of-life. The following end-of-life scenarios are also considered and modelled as appropriate for each material:

- Reuse – glass fibre, mineral wool, aerogel, VIP (filler), cork, sheep’s wool, cotton
- Recycling – PUR, aerogel, cork, sheep’s wool, cotton
- Composting – cork
- Incineration with energy recovery – VIP (film)
- Landfill – PUR, glass fibre, mineral wool, aerogel, VIP, cork, sheep’s wool, cotton

The first 2 scenarios are preferable in a Circular Economy; unfortunately the polyester binder in the sheep’s wool and the various unknown additives in the cotton insulation make them unsuitable for straight forward composting. Energy from waste was considered as an end-of-life scenario but mineral wool and fibre glass are unsuitable because they are in essence fire resistant (although they soften at temperatures above 1200^{o}C); on the other hand PUR and other polymers have a reasonable calorific value when incinerated (12 kW/kg) in comparison with cork (7.3kW/kg) and cotton and sheep’s wool (4.6 kW/kg) but reliable emissions details were not available for some of these materials. Consequently this scenario is very limited in this case study but will be included in future studies. In this model the PUR is recycled using pyrolysis to produce oil, gas and char residue. The mineral wool and VIP core cannot be recycled but in the model the filler is repacked and reused; the VIP film is a laminate and very difficult to recycle so it is incinerated with energy recovery. Landfill is included as a benchmark with which to compare the impact of the other ‘circular’ life cycles and the energy inputs and outputs are based on the standard UK mix.

In this simplified LCA the numerous inputs, outputs, and impacts were assessed using SimaPro LCA software, the Eco-indicator 99 method and (where possible) Ecoinvent Database. Weighted results are presented as Ecopoints so that dissimilar impacts can be easily compared. The datum for this unit (1000 Ecopoints) derives from the average impact of 1 European person per year. Uncertainties in this study are also limited by weighting the results with the default Hierarchist weighting set, i.e. the effect of impacts are considered over a medium timescale, it is predicted that many problems can be avoided through proper policies, and inclusion of evidence / data is based on expert consensus.

Results – Life Cycle Assessment

Figure 2 clearly shows that the impact of operational energy use far exceed that of the various types of insulation, although this model excludes end-of-life treatment. The impact of the natural materials is higher than all synthetic materials apart from the VIPs, which is due to land use although this ratio changes when recycled or reused. The cork and the sheep's wool have the highest levels of thermal conductivity and thus operational energy inputs which contributes to the high overall impact. Conversely although the impact of the VIP product has a higher impact than the other synthetic materials, these panels have the lowest level of thermal conductivity and consequently the lowest overall combined impact.

Figure 2: Combined impact of different types of insulation and operational energy over 5years.

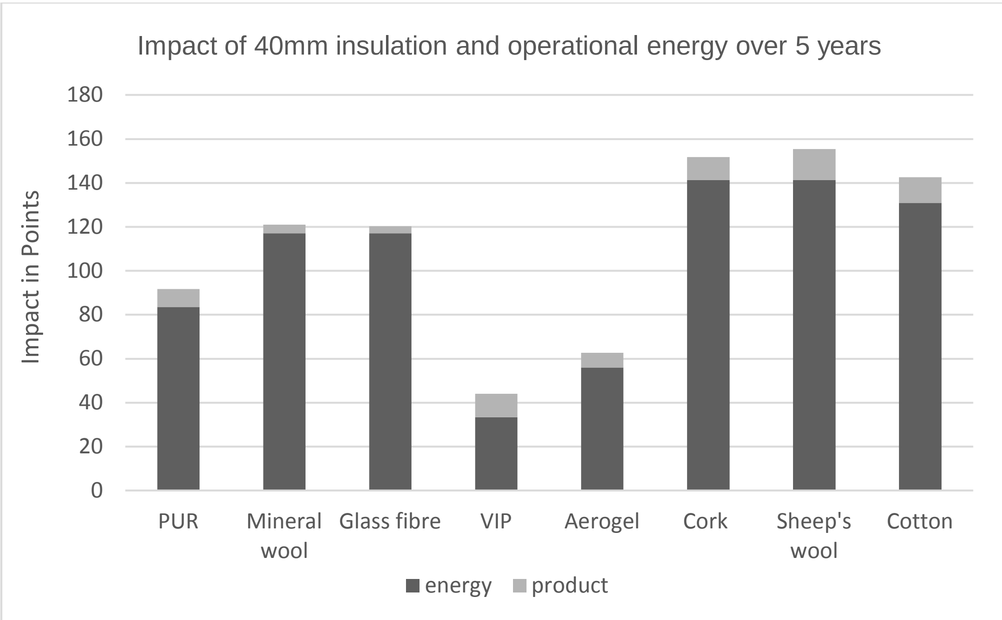
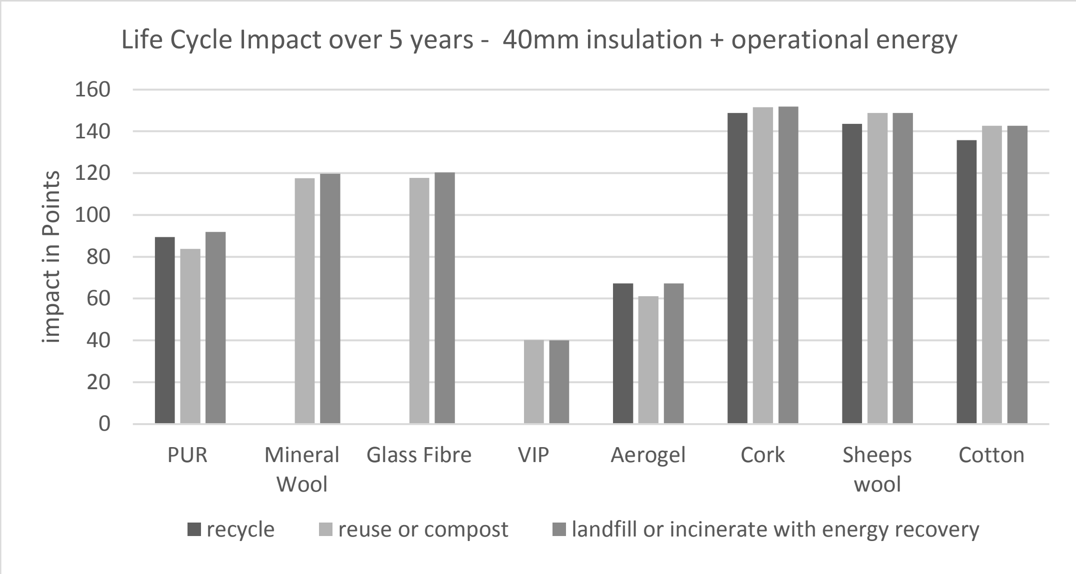


Figure 3 shows that the inclusion of end-of life scenarios increases overall impact for all materials but once again the impact of energy use exceeds that of the product. In all cases sending the insulation to landfill at end-of-life has the highest impact because the materials are literally wasted although the impact varies according to the decomposition, and while some materials are inert others emit greenhouse gases. In the case of aerogel, reuse is seen to have a lower impact than recycling while the opposite is true in the case of the other materials; this is due to the differing inputs and outputs of the various recycling and reuse processes.

It is stated above that the adhesive properties of PUR insulation in RDCs make reuse impossible; however PUR sheet that is used in the construction industry can be reused providing that it is uncontaminated. This highlights the benefits of reusing PUR and the need to investigate potential means of reducing or preventing adhesion even though this will increase the life cycle impact of reuse.

Figure 3: Combined impact of different types of insulation and operational energy over 5years.



Economic factors

The cost of insulation is based on current wholesale costs and varies considerably as seen in table 2, which also shows the difference in functional life. It has already been explained that this is influenced by compaction, humidity, fungal growth and durability. Some materials can be repaired and could be reused and kept in circulation beyond the life of the RDC providing that they aren't contaminated; others can be recycled.

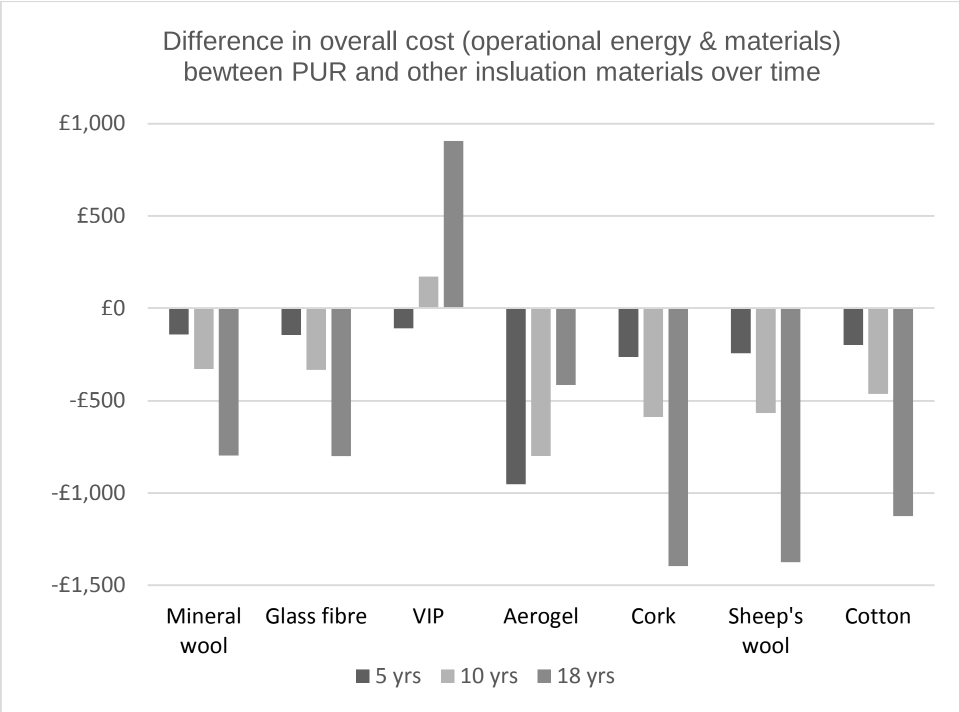
Table 2: Cost of insulation materials per m^2 and functional life in situ.

Insulation material	Cost 40mm thick / m^2	Average functional life in years
PUR	£4.20	100
Mineral wool	£2.30	90
Glass fibre	£3.70	80
VIP	£90.00	18
Aerogel	£311.00	45
Cork	£10.00	100
Sheep's Wool	£3.90	60
Recycled Cotton	£2.90	15

Retail culture has changed and evolved dramatically since the introduction of supermarkets and more recently on-line sales. It is therefore difficult to predict what the 'farm to fork' and cold chain will include in the long term future but it is undoubtable that cool, chilled, and cold food storage will still be required. Assuming that RDCs are properly maintained and components are upgraded product life will be 20 years and over. Although longer than the functional life of cotton (15 years) the high level of thermal conductivity and related operational energy mean that it is unlikely that it will be used for refrigeration, VIP life is also shorter than that of other materials but the low thermal conductivity and energy use could make this technology an attractive option so product life in this model is assumed to be 18 years.

Costs over life are calculated by adding the cost of 1 x 3.42m^2 panel to that of operational energy. It is reasonable to expect that energy costs will increase throughout the life of the RDC but it is difficult to predict the rate and size of increase. Between 2005 and 2015 the cost of electricity in the UK industrial sector increased by 7% per year on average (DECC, 2015) and future costs are therefore based on this rate of increase. The difference between the overall costs (panel + operational energy) of a PUR panel and the 7 other types of panel are calculated to ascertain whether there is any economic advantage in materials' substitution; the results are shown in figure 4:

Figure 4: The difference in overall costs between PUR and other insulation materials



Results – overall life time costs

Over 5 years the combined costs (materials + operational energy) of substitute insulation are higher than those of PUR; this is also the case after 10 and 18 years for all materials other than VIPs. As previously stated this is due to the low level of thermal conductivity and related operational energy inputs.

The cost of insulation will be passed on to customers and in an already competitive market place, lower costs in combination with long functional life make PUR, mineral wool, glass fibre, cork and sheep's wool attractive options. The overall environmental impact of these products is considerably higher than that of the more expensive VIPs however which makes materials selection difficult. This is further compounded by length of functional life (where materials could be reused or recycled and used in future products) and uncertainty about the value of such materials in the future.

Conclusion and discussion

The above research highlights some issues facing designers, engineers and manufacturers as they begin to develop products and services for a Circular Economy.

The first case study shows the impact of the product only (i.e. without end-o-life scenario) and if materials selection were to be guided by this then mineral wool or glass fibre would be the preferred choice. When operational energy is considered in conjunction with materials however those that are initially unfavourable (VIPs) are definitely the preferred choice because of their excellent insulation properties. This is also true when various end-of-life scenarios are considered even though as yet there is no recycling infrastructure for VIPs. This model assumes that they are not damaged before the end of functional life; if they were damaged they would have to be replaced which would negate a considerable amount of operational energy cost savings.

Unless customers want to be seen to engage in sustainable business practices or are visionary enough to recognise the long term economic benefits that derive from investing in these emerging technologies it is unlikely that they will be adopted at present. Adoption of more efficient insulation could be encouraged through legislation or through alternative business models like leasing. In this case the higher product costs for the customer could be spread over time although the manufacturers would have to ‘foot the bill’ initially; the lower operating costs could make an RDC with VIP insulation attractive to customers and therefore to potential investors in leasing schemes. Furthermore this model could overcome some of the barriers about buying remanufactured RDCs because the

Even though the life cycle impacts of PUR are higher than those of VIPs and aerogel, the lower costs make PUR insulation an attractive choice now and in the immediate future. The potential for reuse could be realised if adhesion to the steel panels is significantly reduced or eliminated, which could also reduce the cost of re-manufacture and eventual disposal. The panels will have to be redesigned and tested to ensure that they are structurally sound but this will be a worthwhile investment.

Finally further case studies should include assessment of the economics of various end-of-life scenarios and labour costs at all stages of product life as well as potential increases in the cost of materials and manufacturing processes. Nevertheless this is an important case study that illustrates the complexity of decision making towards the development of a Circular Economy.

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