Available online at www.sciencedirect.com
SCIENCE DIRECT®
Resources, Conservation and Recycling 44 (2005) 37–50
Resources Conservation & Recycling
www.elsevier.com/locate/resconrec

Improving recyclability by design: a case study of fibre optic cable

Elizabeth Wright[a,b], Adisa Azapagic[a,*], Gary Stevens[b], Warren Mellor[a,b], Roland Clift[a]

[a] *Centre for Environmental Strategy, School of Engineering (D3), University of Surrey, Guildford, Surrey GU2 7XH, UK*
[b] *Polymer Research Centre, University of Surrey, Guildford, Surrey GU2 7XH, UK*

Received 8 December 2003; received in revised form 20 September 2004

Abstract

Producer responsibility and take-back legislation in Europe place responsibility on the manufactures for the recovery and recycling of end-of-life products. This will inevitably require the manufacturers to rethink the way products are designed and manufactured in order to improve their recyclability. This paper illustrates on the case of a fibre optic cable how this can be achieved in a practical and relatively easy way, leading to both environmental and economic benefits. The case study compares the current design the 96 fibre optic cable with several proposed design modifications with the aim of identifying the design option that would enable an easy end-of-life disassembly and recycling of component materials. The designs are evaluated on a life cycle basis for both economic and environmental impacts using the CHAin management of Materials and Products (CHAMP) methodology. CHAMP combines elements of process and design engineering with life cycle approaches to enable the user to explore technical, economic and environmental consequences of different material, process and technological options, including material recovery and recycling. CHAMP is therefore particularly well suited for addressing the requirements of the take-back and producer responsibility legislation.

The results of LCA and life cycle costing obtained by using CHAMP show that cable re-design can reduce the environmental impacts by between 30 and 60% and can lead to a 40% reduction in economic costs. This is achieved by changing the internal structure of the cable, by removing some of the cable components (e.g. aluminium and organic gels) and by recycling some of the materials. Transport (including reverse logistics), processing and landfill also contribute to the overall impacts,

* Corresponding author. Tel.: +44 1483 689170; fax: +44 1483 686671.
E-mail: a.azapagic@surrey.ac.uk (A. Azapagic)

0921-3449/$ – see front matter
doi:10.1016/j.resconrec.2004.09.005

but their contribution is less significant than that from the materials used to manufacture the cable.

Keywords: Environmental impacts; Life cycle assessment; Life cycle costing; Design for recyclability; Material recycling; Fibre optic cable

1. Introduction

European legislation is increasingly being based on the ‘take-back’ and ‘producer responsibility’ concepts – it places sole responsibility on the manufacturers for the recovery and recycling of products at the end of their useful life. Typical examples of the EC producer responsibility legislation include the End-of-life Vehicle (ELV) Directive (EC, 2000) and the Waste Electronic and Electrical Equipment (WEEE) Directive (EC, 2003). For many manufacturers, this is a responsibility that they have not previously experienced. Historically, products have been designed with function and cost as the main drivers and consideration of end-of-life product and material recovery has been limited. However, as the producer responsibility obligations are shifting the focus towards the end-of-life considerations, to reduce the costs of recovery and recycling and remain competitive, the manufacturers must now start thinking about designing products for take-back and recycling. This will require a life cycle approach whereby the materials and components that are chosen at the beginning of a product’s life cycle will enable an easy disassembly and reuse of these materials at the end of its useful life (Azapagic, 2001). The ultimate aim is to design more sustainable products by building into design the possibility for ‘cascaded’ reuse of materials in a number of different life cycles (Azapagic, 2002; Azapagic et al., 2003).

In light of the producer responsibility requirements, many manufacturers are now reconsidering their current product design practices with a view to designing for the ease of dismantling and recyclability. This paper illustrates, for the case of a fibre optic cable, how this can be achieved in a practical and relatively easy way, leading to both environmental and economic benefits. The case study presented here compares the current design of the 96 fibre optic cable with several proposed design modifications with the aim of identifying design options that would enable an easy end-of-life disassembly and recycling of component materials. The designs are evaluated with regard to both economic and environmental impacts using the CHAin management of Materials and Products (CHAMP) methodology.

The CHAMP methodology is detailed elsewhere (Mellor et al., 2002) but in brief, it is a methodology and a modelling platform comprising a set of inter-connected tools and approaches, including Life Cycle Assessment (LCA), Design for the Environment (DfE) and Life Cycle Costing (LCC). CHAMP is based on a life cycle approach, but goes beyond conventional LCA by enabling modelling of the ‘cascaded’ reuse of materials in multiple life cycles, based on specified material performance criteria. For these purposes, materials are characterised in CHAMP by a set of technical performance parameters, termed utilities. The appropriate ‘acceptance’ criteria (e.g. material strength, optical transparency, the level of contamination by other materials, etc.) are used to determine whether a material is suitable for a specific use or reuse and to guide selection of materials for specific applications.

Geographical location is also treated as a utility to enable logistics – both distribution of products and collection of used products or waste – to be incorporated within the same modelling framework. Processing, transport and use are treated as activities through which a material can pass. The costs and environmental impacts of activities are assessed on a life cycle basis by considering the complete supply chain of materials and energy used by each activity. Using the approach developed by Azapagic and Clift (1999), CHAMP also enables multi-objective systems optimisation on environmental and economic objectives, subject to technical and other constraints. The set of Pareto-optimal options generated by the model can then be used to explore the trade-offs between different technical, economic and environmental criteria and to identify the 'best' option.

One of the advantages of CHAMP is its flexibility, allowing choice of the most appropriate tools within the modelling platform, to suit the particular application. For example, for the case study presented here, the CHAMP tools used include DfE, LCA and LCC. Their application and the findings of the case study are discussed next.

2. Designing for recyclability – the fibre optic case study

Currently, material recovery and recycling of the 96 fibre optic cable are difficult for technical and economic reasons. This is mainly due to the presence of several organic gels and fused polymers that are commingled with metals in the cable, which makes separation of the components difficult but also causes contamination of some components. Therefore, the aim of this study has been to identify the design options which would enable easier dismantling and recycling of the cable components but would not be economically prohibitive. For these purposes, two alternative designs have been compared with the current cable design on the life cycle environmental and economic performance using the CHAMP methodology.

2.1. Current cable design

As shown in Fig. 1a and b, the composition of the 96 fibre optic cable is relatively complex, involving the following components and materials:

- optical fibres (1.5%, w/w) and copper wire (2.5%, w/w) used for signal transmission;
- linear low density polyethylene (LLDPE) used as the outer sheathing (40 w/w);
- polybutylene terephthalate (PBT) used for primary sheathing of the optical fibres (13%, w/w);
- steel used as a central strength member to increase the strength of the cable (23%, w/w);
- organic gel for loose tube filling and as the interstitial gel (14%, w/w);
- aluminium as the moisture barrier (4.5%, w/w);
- paper to wrap the cable and for the ripcord (1.5%).

Each of these materials must satisfy certain performance criteria or 'utilities' to enable the cable to function properly. Some of the key utilities that have been modelled in this case study by CHAMP are listed in Table 1. It should be noted that the utilities do not change in the cable manufacturing process; however, they may change during cable use and material reprocessing for recycling. It is therefore important to determine the material utilities at the

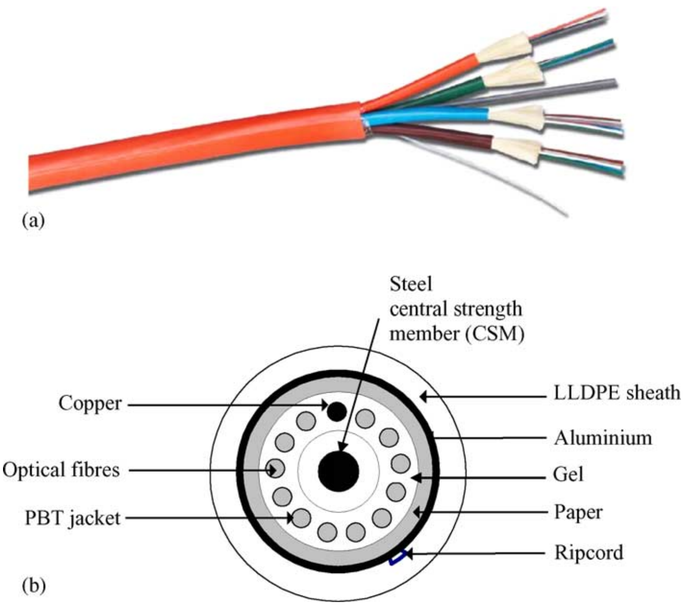

Fig. 1. (a) An example of a fibre optic cable. (b) The components of the fibre optic cable (“loose tube” design).

end-of-life to be able to identify the appropriate options for cascaded use for the materials of interest.

The life cycle of the 96 fibre optic cable is illustrated in Fig. 2. The figure shows all the activities from ‘cradle to grave’, including the extraction of primary resources and

Table 1
Key utilities of the cable component materials

Component	Material	Key utilities	Units
Central	Steel	Tensile modulus	GPa
Steel member		Min. breaking load	kN
		Diameter	mm
Primary sheath	Polybutylene terephthalate (PBT)	Melt flow index	cm^3/10 min at 250 °C
		Moisture content	%
		Modulus	GPa
Fibre colouring	Ink	Viscosity	Pa s at 30 °C
		Hardness after curing	Shore A
PBT tube filling gel	Organic gel	Softness at low temperature	°C
		Flow at high temperature	°C
Interstitial gel	Organic gel	Run temperature	°C
Ripcord	Cotton	Tensile strength	MPa
ID tape		Printability	
Moisture barrier	Aluminium	Peel strength from sheath	N
Outer sheath	LLDPE	Melt flow index	cm^3/10 min at 210 °C
		Brittleness temperature	°C
		Env. stress cracking	

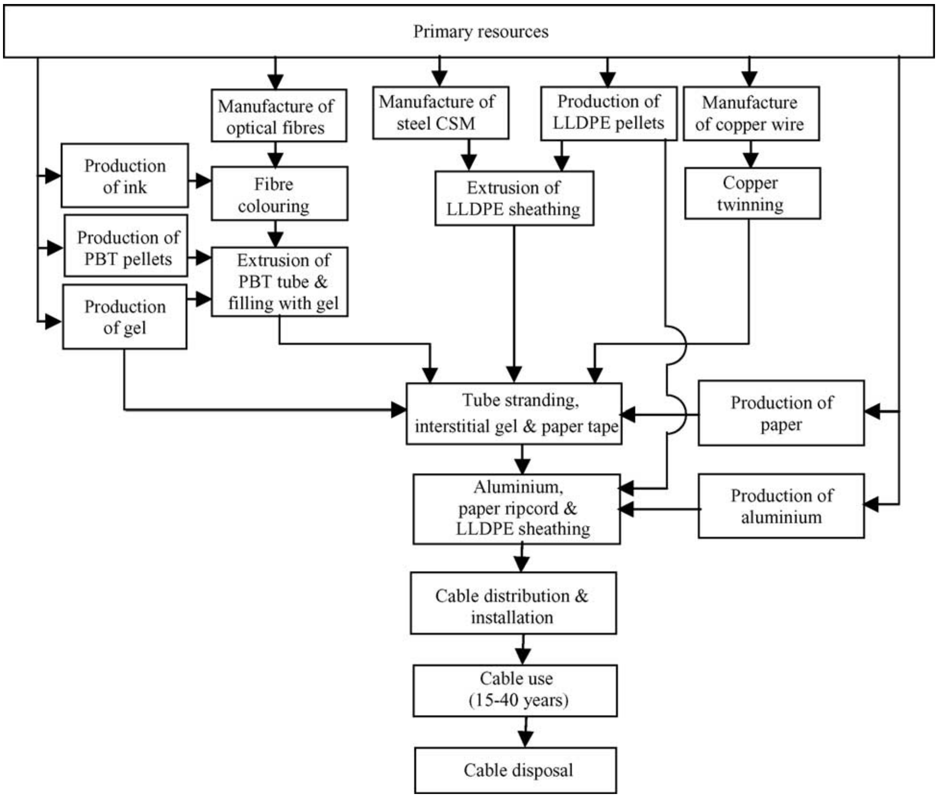

Fig. 2. Flow diagram of the life cycle of the fibre optic cable.

manufacture of the component materials; the cable manufacturing process; the use of the cable and, finally, its end-of-life disposal.

The cable manufacturing process itself involves several operations. First, the steel is used as a central strength member (CSM) to reinforce the cable. The CSM consists of a compressed steel strand onto which the LLDPE jacket is extruded. The next step is the colouring of fibre optics with various inks for the ease of identification during their use, after which a polybutylene terephthalate (PBT) tube is extruded loosely over a bundle of eight fibres (this design is known as “loose tube” as opposed to “tight-buffered” cable). The loose tube of fibres is filled simultaneously with an organic gel that acts as a moisture barrier. The fibre optic tubes are then twisted around the central strength member (CSM) together with the twinned copper to a required length. This process is known as stranding. A further hydrophobic gel is applied during stranding to prevent water penetration. Paper is then added to wrap the whole cable construction. This is followed by the addition of a ripcord, an identification tape and the aluminium moisture barrier. Finally, a LLDPE jacket is extruded to protect the cable assembly and to bond the outer sheath to the moisture barrier.

The cable is then distributed for installation after which it remains in use for 15–40 years. At the end of its service life, it is normally landfilled as its recycling is difficult. As already mentioned, to increase the recycling potential of the cable, two design changes to the current design have been considered; these changes are described below.

2.2. Cable re-design

The first re-design option considered is the removal of the bonding between the aluminium and the LLDPE outer sheathing. The total mass of material inputs in this design remains the same but the potential to recycle aluminium and LLDPE is increased as the absence of the physical bonding created by the extrusion of the outer LLPDE sheathing makes it easier to separate these two materials.

The second re-design option involves removal of the aluminium moisture barrier and organic gel. Several experiments carried out in conjunction with this study have proved that it may be possible to remove the moisture barrier without impairing the function of the cable. This would enable much easier dismantling of the cable and would therefore increase the potential for recycling. Furthermore, this would lead to a reduced use of materials and to a simplification of the manufacturing process. Removal of all gels used in the cable design has also been considered since this eliminates contamination and can significantly improve the quality of the recyclate. Neither of the re-design options affects the cable performance characteristics.

The life cycle of the re-designed cables is similar to the cable used currently (see Fig. 2), except for two life cycle stages: the manufacturing process and end-of-life disposal options. The main difference in the manufacturing process is that in the first re-design option the bonding between the aluminium and LLDPE sheathing is eliminated while in the second, the use of aluminium and organic gel is avoided.

However, the differences in the end-of-life disposal options between the current and new designs are more substantial than the differences in the manufacturing process. As already mentioned, fibre optic cables can currently only be landfilled at the end of their useful life because their recycling is not feasible. On the other hand, cable re-design considered here would enable recovery and recycling of different materials, including steel, aluminium and plastics. These materials together represent around 67% of the cable weight so that their recovery and reuse would create a potential for significant savings in the virgin material use, potentially leading to a reduction in environmental impacts and economic costs. Aluminium and steel could be remelted and used for new cables or in other ‘cascaded’ applications. The plastic materials could be recycled mechanically either in the same or a different application or they could be incinerated to recover energy. Some of these end-of-life options are illustrated in Fig. 3.

The following section compares the life cycle environmental impacts of the current and new cable designs.

2.3. Environmental evaluation of different designs

The cable system and the system boundary considered in this study are shown in Figs. 2 and 3. The basis for comparison (or, using the LCA terminology, the functional

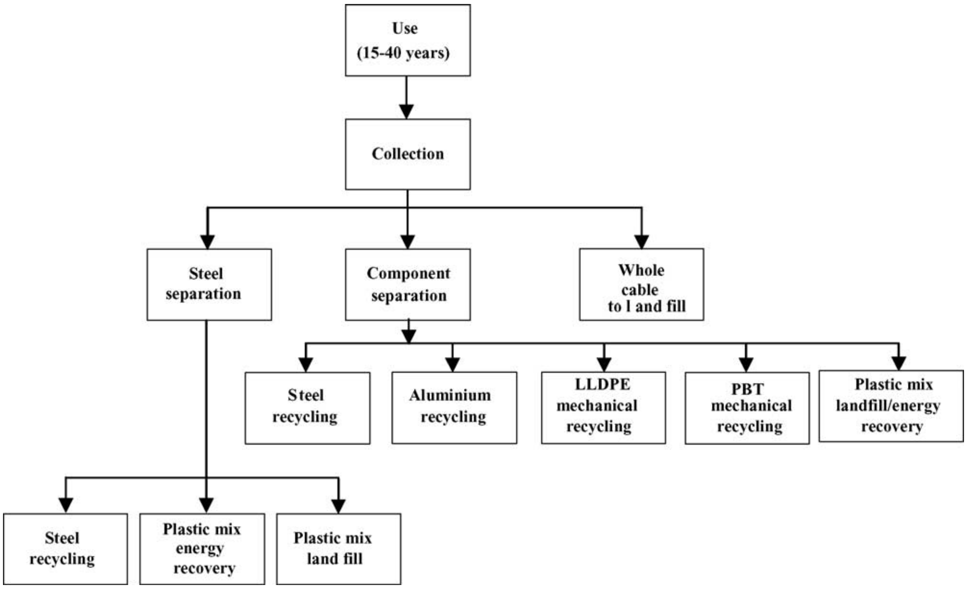

Fig. 3. End-of-life options for different fibre optic cable designs.

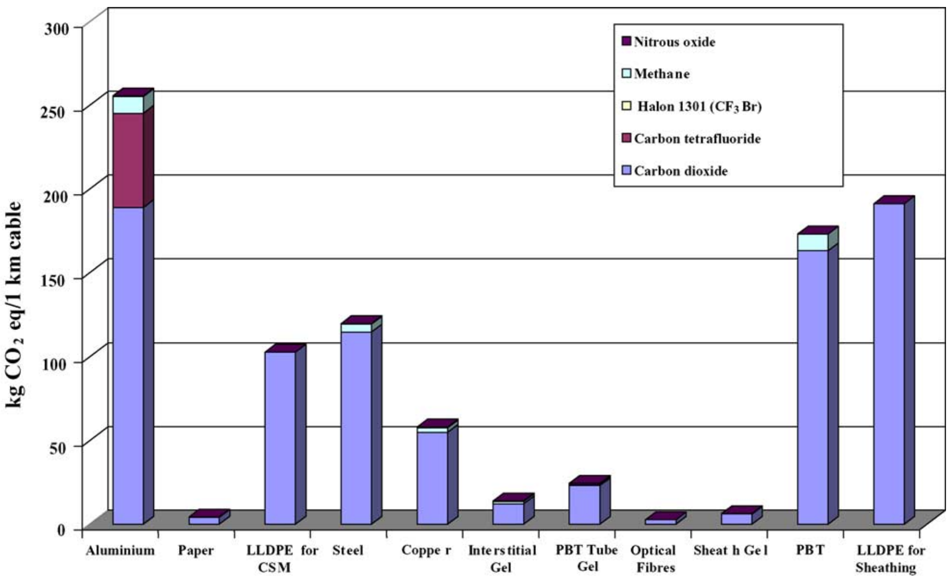

Fig. 4. Global warming potential for the current cable design showing the contribution of different materials to the total environmental impact.

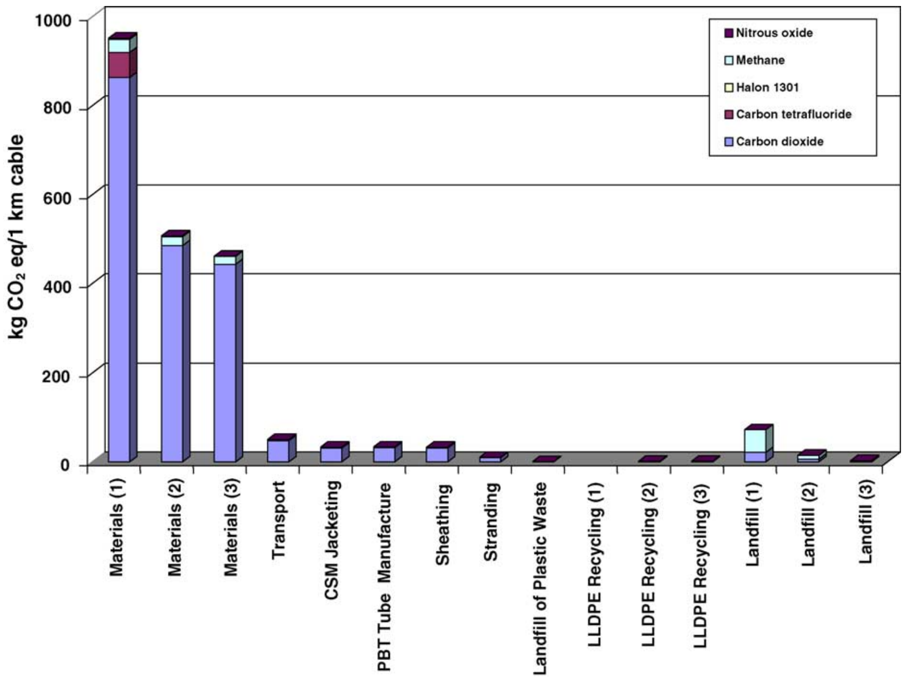

Fig. 5. Comparison of global warming for different cable designs (basis for comparison: 1 km of cable).

unit) is 'the production and recovery of 1 km of fibre optic cable'. The study is based in the UK and the cable manufacturing data used are site specific, based on current practice. Both upstream, manufacturing and reverse logistics and the associated environmental impacts have been considered in this study.

The upstream LCA data for energy, fuels and transportation have been obtained from the Swiss Agency for the Environment, Forests and Landscape (SAEFL, 1998) while the LCA data for the materials used in the cable system are taken from publicly available databases (Frischknecht et al., 1996; Habersatter and Widmer, 1991) and from the DEAM database (Ecobilan, 1999).

The data for the production of optical fibres have not been available due to confidentiality. Instead, generic glass data have been used to gauge the significance of the glass component in the cable in terms of the environmental impacts. It should, however, be noted that the manufacture of optical fibres is much more energy intensive than the glass production so that some of the impacts, particularly those related to energy consumption such as global warming, are probably lower here than they would be in reality.

In terms of the end-of-life options, it has been assumed that, due to the presence of organic gels and the bonding between the aluminium and the LLDPE sheath in the current cable design, it is not possible to recover and recycle any of the cable components and therefore the cable is sent to landfill. The removal of the bonding between the aluminium and the outer LLDPE sheath in the first re-design option allows these two materials to be recycled.

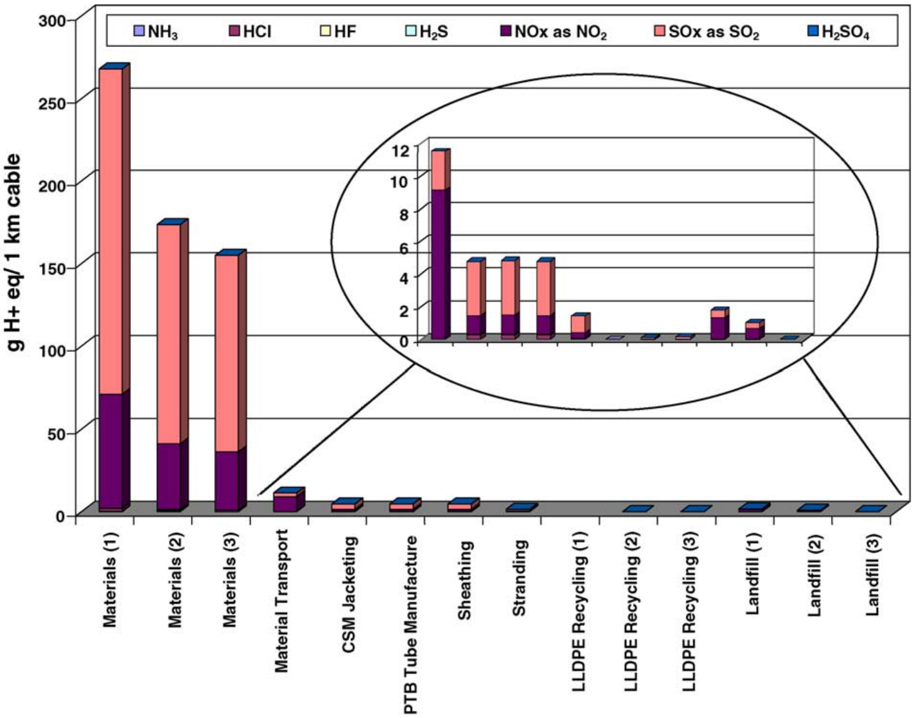

Fig. 6. Comparison of acidification for different cable designs (basis for comparison: 1 km of cable).

For illustration, closed loop recycling of these materials back into the cable manufacture has been considered to evaluate the environmental effects of the reduction in virgin material input in to the system. Finally, the removal of the aluminium and the gel altogether in the second re-design option both reduces the input of materials and enables recovery and recycling of components. As in the first re-design option, closed loop recycling of LLDPE has also been investigated; in addition to this, cascaded use of LLDPE into polymer film has also been considered.

The LCA study was carried out using CHAMP and the aforementioned databases. The problem-oriented approach[1] (Guinée et al., 1993) was used to calculate the environmental impacts of different cable designs. For illustration, only selected results are shown and discussed here. The different designs are represented by the following notation in the figures:

(1) Current design with landfilling of whole cables.
(2) Removal of the bonding between aluminium and LLDPE with closed loop recycling of both materials.

[1] In the problem-oriented approach, the impacts are classified according to the environmental problems that are caused by a particular human activity; examples of impacts include global warming, acidification and ozone depletion.

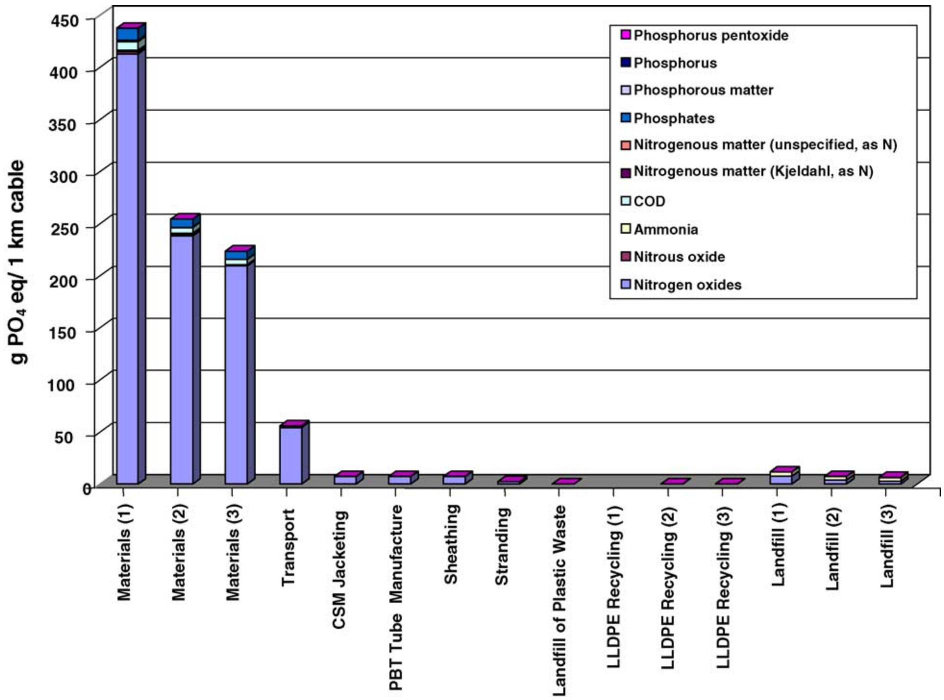

Fig. 7. Comparison of eutrophication for different cable designs (basis for comparison: 1 km of cable).

(3) Removal of aluminium and gel with *closed loop* recycling of LLDPE.
(4) Removal of aluminium and gel with *cascaded* recycling of LLDPE (as polymer film).

However, before comparing the environmental impacts of different designs, it is interesting to examine the environmental impacts of the current cable design and to identify the life cycle stages with the largest contribution to the impacts. As an example, Fig. 4 shows the results for global warming. It is apparent from the figure that the largest contribution to this impact is from the life cycles of the materials used to assemble the cable, i.e. the aluminium, plastics, steel and copper. Together, they contribute to 75% of the total global warming impact associated with the life cycle of the current cable design. A similar trend is noticed for the other environmental impacts (not shown here). This points to the conclusion that the reduction in the use of materials and their recycling as proposed in the two re-design options might lead to significant environmental improvements.

The comparison of selected environmental impacts for different cable designs shown in Figs. 5–7 would indeed suggest that significant environmental improvements could be achieved with new cable designs. As shown in Fig. 8, the reduction in the environmental impacts ranges between 30 and 60% and is mainly due to the reduced use of materials and due to crediting the system for material recycling (the ‘avoided burdens’ approach was used to credit the cable system for both closed loop and cascaded recycling). Fig. 8 also shows

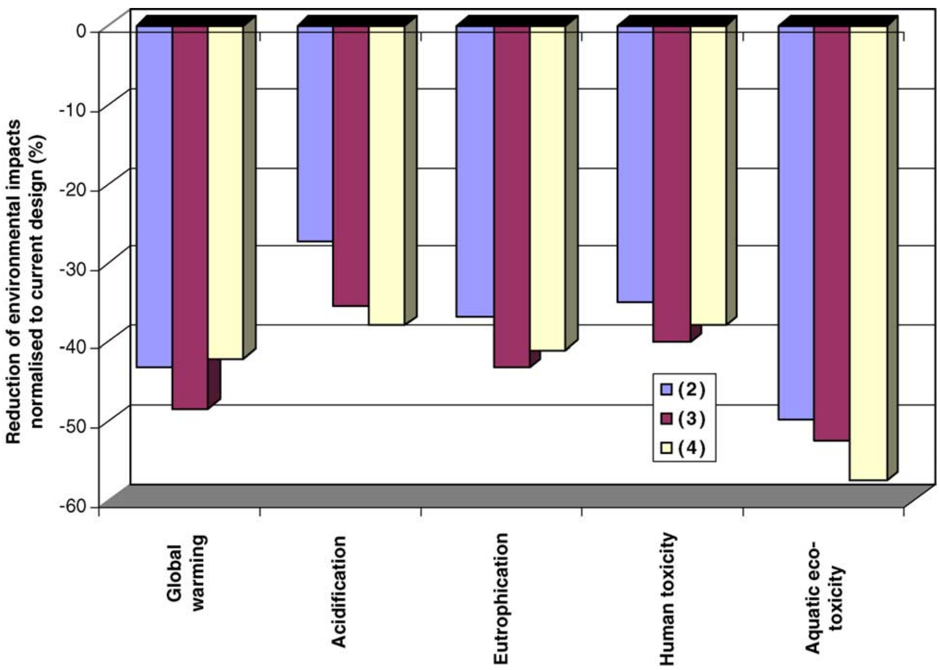

Fig. 8. Environmental benefits from cable design changes and different end-of-life options (basis for comparison: 1 km of cable).

that, overall, there is little difference in the environmental impacts between the closed and cascaded recycling of LLDPE which means that, under the assumptions made in this case study, both options would yield comparable environmental benefits.

The analysis of the environmental impacts points to the conclusion that the removal of the gels from the cable construction would not significantly reduce the overall impact from the system. However, the absence of the gel in the fibre optical cable enables recovery of the component materials such as LLDPE, PBT, aluminium and steel.

The LCA results also indicate that the greatest reduction in impacts can be achieved in the first re-design option (no bonding between aluminium and the LLDPE sheathing) if the two materials are recycled and reused. Of the two materials, recycling of aluminium shows the greatest potential for the reduction of environmental impacts. The reason for this is that the production of virgin aluminium is an energy intensive process so that the use of recycled aluminium can save up to 95% of the overall energy used. Because of this large saving (avoided burden) from aluminium recycling, the overall benefit of complete removal of aluminium from the cable in the second re-design option would appear to be marginal; the same trend has been noted for some other impact categories such as acidification and eutrophication. However, given an increasing trend in the use of aluminium, as well as the growing telecommunication networks world-wide, the removal of this material from optic cables would obviously be advantageous.

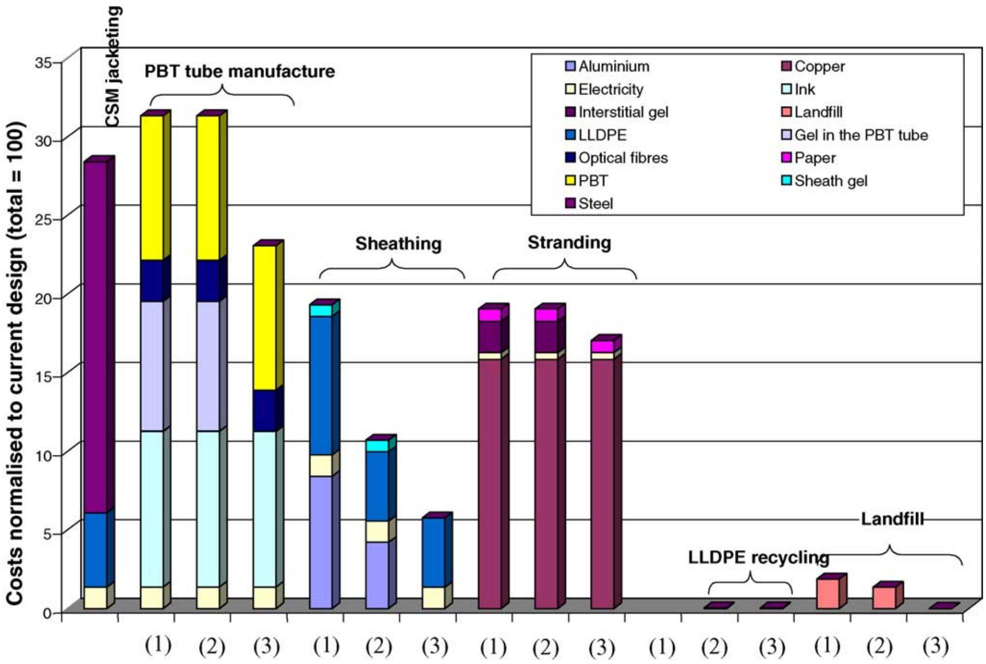

Fig. 9. Cost comparison for different cable designs (basis for comparison: 1 km of cable).

2.4. Economic evaluation of different designs

The results of the life cycle economic evaluation of different design options are shown in Fig. 9. Note that due to data confidentiality, it has only been possible to show relative results, normalised to the current cable design. Cascaded recycling of LLDPE has not been analysed on economic impacts due to the lack of data; furthermore, following the results of environmental evaluation, it is likely that the cost difference between the closed loop and cascaded recycling would be marginal.

The extent to which economic benefit is gained from changing the cable design depends on a number of variables, including the market price of virgin and raw materials, energy costs, costs of logistics and recycling and landfill charges. As shown in Fig. 9, the largest contribution to the costs in the cable system is from the material inputs. By comparison, contribution to the total costs of energy (electricity) used for cable manufacturing, LLDPE recycling and the landfill charges (currently £ 35 t^{-1} waste) are marginal. For the purposes of this study, it has been assumed that the cost of polymer (LLDPE) recyclate is half that of virgin polymer.

Therefore, this would also suggest that changes in the cable design aimed at reducing the material inputs could lead to a significant reduction in costs. As Fig. 9 shows, the largest cost savings are achieved in the second re-design option, where the use of aluminium and the gel is avoided altogether. A total saving of up to 40% can be expected for this design modification.

3. Conclusions

This case study demonstrates the benefits of using life cycle product design approaches to identify areas for improvements in both environmental and economic performance. The results of LCA and the life cycle costing obtained by using CHAMP show that a large proportion of environmental impacts and costs are caused by the materials used in the cable manufacture. Transport, processing and landfill all play a role in increasing the overall impacts, but their contribution is less significant. These results would suggest that the attempts to improve the overall environmental and economic profile of the cable's life cycle should concentrate on design changes to include reduction of the quantities and number of material used as well as recycling of these materials where feasible. Putting too much effort into improving the efficiency of processing activities, or trying to reduce the distance over which the materials are transported, would in this case result in marginal improvements.

Removing the material components altogether is clearly the most beneficial approach to impact and cost reduction, although recycling is shown to be almost as effective in terms of environmental performance. If used in conjunction with each other, these two approaches would clearly result in greater economic and environmental benefits.

The extent of the economic benefit from changing the cable design depends on the market price of virgin and recyclate materials, landfill charges and energy costs. Here, certain assumptions have been made with regard to these variables and the results obtained are therefore only valid under these assumptions. In reality, the cost of recycled materials may not be as low as half that of the virgin materials as assumed here; however, removal of materials and simplification of the design will always result in a more cost-effective alternative.

References

Azapagic A. Design for optimum use of resources – cascaded use of materials. In: Conceicao P, Gibson D, Heitor MV, Sirilli G, Veloso F, editors. Knowledge for Inclusive Development, Quorum Books. Connecticut: Westport; 2001. p. 435–48 Chapter 18.

Azapagic A. Life cycle assessment: a tool for identification of more sustainable products and processes. In: Clark J, Macquarrie D, editors. Handbook of Green Chemistry and Technology. Oxford: Blackwell Science; 2002. p. 62–85.

Azapagic A, Emsley A, Hamerton I. Polymers, the Environment and Sustainable Development. Chichester: Wiley; 2003.

Azapagic A, Clift R. Life cycle assessment and multiobjective optimisation. J Cleaner Prod 1999;7(2):135–43.

EC. Directive 2000/53/EC of the European Parliament and of the Council of September 18, 2000 on End-of-life Vehicles. Official Journal of the European Communities L269; October 21, 2000.

EC. Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on Waste Electrical and Electronic Equipment. Official Journal of the European Communities L37/24; February 13, 2003.

Ecobilan. DEAM LCA Database; 1999.

Frischknecht, R. et al. (Eds.). Okoinventare von Energiesystemen – Grundlagen fur den okologischen Vergleich von Energiesystemen und den Einberzug von Energiesystemen in Okobilanzen fur die Schweiz, ETHZ/PSI. 3rd ed. Bern: ENET, 1996.

Guinée, J.B. et al. (Eds.). Life cycle assessment: guide and background. Leiden: CML; 1993.

Habersatter, Widmer. Okobilanz von Packstoffen, Stand (1991) Schriftenreihe des BUWAL; 1991. p. 132.

Mellor W, Wright E, Clift R, Azapagic A, Stevens G. A mathematical model and decision-support framework for material recovery, recycling and cascaded use. Chem Eng Sci 2002;57:4697–713.

SAEFL. Life cycle inventories for packagings. vol. I&2. Environmental Series No. 250/I&2. Swiss Agency for the Environment, Forests and Landscape (SAEFL); 1998.