Life-cycle assessment of PVC-U joinery profiles

Leslie Flanagan[2] BSc (Hons) PhD

.

School of the Environment, University of Brighton, Cockcroft Building, Lewes Rd, Brighton BN2 4GJ UK, Phone:+44 (0)1273 642388 Fax:+44 (0)1273 642285 E:mail: l.flanagan@brighton.ac.uk

1.0 INTRODUCTION

The specification and use of polyvinyl chloride (PVC) continues to be an emotive subject. The desire to quantify the impacts associated with the polymer's formation and enduse has gained increased emphasis following publication of the European Commission's horizontal study into the enduse and disposal of the polymer. The released documentation, which include factors affecting mechanical recycling [Plinke 2000] and the behaviour of the polymer in landfill Sites [Argus 2000], have further added to the polemic views of industry and environmentalists. The UK Government's response to the European Comission's Green considered the Best Practical Environmental Option (BPEO) remains unclear for PVC disposal and the industry requires help in order to meet the challenge of sustainable development [DEFRA 2001].

Every function nevertheless has an appropriate end-use that reflects the service life, geographical scope and the reuse and recycling technologies available. Each material application is therefore unique and therefore no common solution truly exists, only guidance. Basic propositions of material re-use over energy expenditure may be considered, with the drivers being either economic gain or a reduction in ecological burden. The issue of the material re-use is therefore controlled by technical, economic and environmental considerations, the combination of which form barriers to change.

Research conducted by the University of Brighton investigated the interactions between polymer reuse and energy burden. The study focused on the application of unplasticised PVC (PVC-U) using a life-cycle assessment (LCA) methodology based on accepted ISO 14041 [1997] practices. The completed study concerned the identification of the systems relating to a distinct life-cycle and examined the impacts against a specific functional unit (FU) in the form of a single casement window, dimension size being 1000x 1000mm with a polymer content in the region of 14kg. The resultant eco-profile is therefore process specific, quantifying all sub-systems associated with the formation and enduse of PVC-U window framing.

Primary data collection focused on profile extrusion, assembly operations, and the re-use of virgin waste. The principal impacts associated with installation and use of the material as a joinery system were also identified. Mass balancing and thermodynamic techniques underpinned sensitivity analysis of the secondary data utilised for polymer formation sub-systems.

Quantification and qualification of the burdens associated with the eco-profile nevertheless remain complex. The interaction between energy and material re-use, with its resultant effects on the environment, compound assessment. The opportunity to examine and review differing enduse scenarios adds to the complexity of data analysis.

2.0 SYSTEM MODEL

The complex interactions experienced during the eco-profile's life-cycle were analysed via the design and implementation of a computer program. The use of a schematic System Model, as illustrated in Figure One, provides a diagrammatic representation of the process investigated in addition to defining the interrelationship between sub-systems. The computer program addresses four criteria that examine energy efficiency in the form of calorific value and conversion of fuel feedstocks; the process energy used by each sub-system; transportation impact attributed to the delivery of polymer and material efficiency - the amount of waste produced.

The System Model identifies the five primary sub-systems associated with the eco-profile's life-cycle and three enduse scenarios. In addition, the impact of material re-use may also be explored via the inclusion of *Re-use of virgin waste* closed-loop recycling sub-system. The System Model displays both process specific and cumulative value of material, energy and transportation requirements. Cumulative airborne emissions, in the form of eight primary pollutants, further illustrate the eco-profile's total burden. The program therefore provides the opportunity to analyse the embodied energy requirement, transportation impact and the energy mix employed within each sub-system and the life-cycle as a whole.

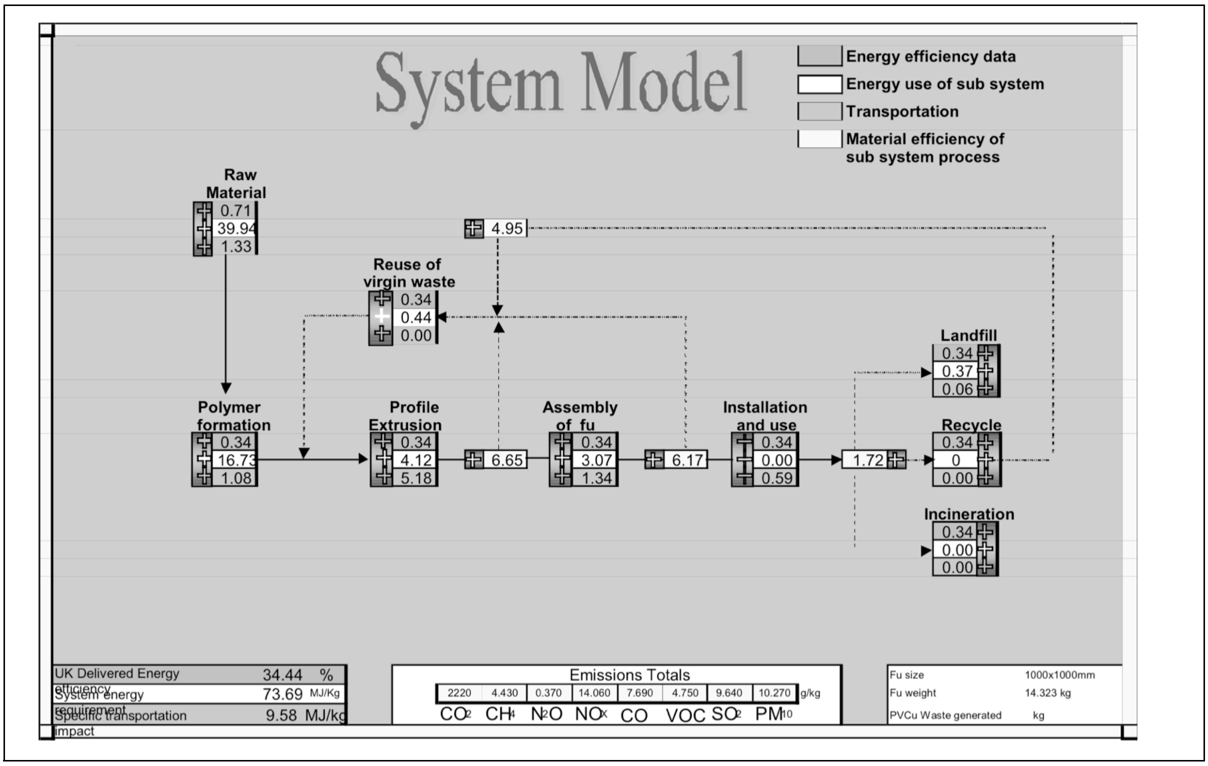
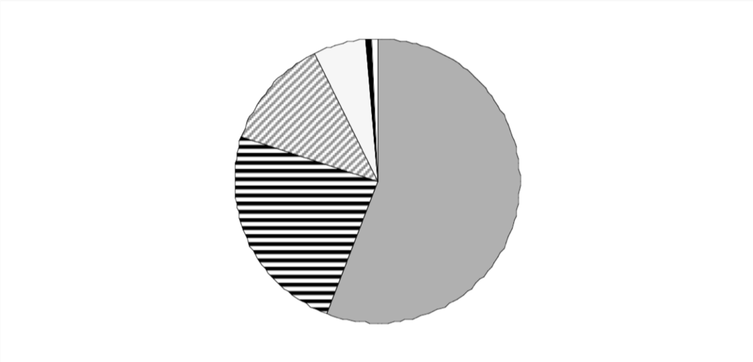


Figure One: System Model Review sheet

The System Model Review Sheet assesses the process specific impacts associated with the formation and output of 1kg mass balanced unit from each sub-system. *Profile extrusion* for example requires 4.12 MJ/kg in process energy. A further 5.18 MJ/kg is expended in the transportation of polymer powder to the extrusion site. Material waste (6.65%) is likewise identified, whilst the conversion efficiency of fuel feedstocks into electricity is assessed to be 34 per cent. The opportunity to model the impacts associated with formation and use of differing geographical regions electricity is thus provided. *Raw Material* formation in Norway therefore records a conversion efficiency of 71 per cent due to the use of hydropower.

The completed inventory analysis of the eco-profile provides a reasoned assessment of the process operations associated with the formation, assembly, use and enduse of PVC-U joinery profiles. The eco-profile cumulative value of 83.27 MJ/kg is comparable with published LCA values which range from 71.55 MJ/kg [IKP 1998] to 138 MJ/kg [Richter 1995]. The energy consumption of each sub-system in isolation and the cumulative impact within the complete life-cycle is identified in Figure Two.

Delivered embodied energy impact of FU profiles



FU: 1000x1000mm full size casement PVC-U window frame
PVC-U material weight: 14.323 kg

Sub-system	Process energy use (MJ/kg)	Transport energy use (MJ/kg)	Total energy use (MJ/kg)	% share
Raw materials	39. 94	1.33	41.27	55.90%
Polymer Formation	16.73	1.08	17.81	24.12%
Profile extrusion	4.12	5.18	9.30	12.59%
Assembly	3.07	1.34	4.41	5.97%
Installation and use	0.00	0.59	0.59	0.79%
Landfill	0.04	0.40	0.44	0.59%
Cumulative impact	**73. 69 MJ/kg**	**9. 58 MJ/kg**	**83. 27 MJ/kg**	
Cumulative CO_2	1425	795 g/kg	2220 g/kg	

Figure Two: Eco-profile delivered embodied energy impact of PVC-U window joinery

2.1 Process energy

The extraction of raw materials extraction together with the formation and transportation of the polymer accommodates 80 per cent of the eco-profile's delivered energy consumption. The energy intensive activities of chlorine formation, the thermal cracking of naphtha and conversion to ethylene dichloride for processing into vinyl chloride monomer subsequently have a significant impact on the life-cycle of the eco-profile. Process allocation and delivered energy efficiency nevertheless alleviate the total environmental burden. Further, the high sub-system value is partly attributed to the cumulative impact of waste from downstream processes, which increase sub-system process energy use by 13 per cent. Transportation impact is likewise increased.

Conversion of the polymer powder into joinery profiles and their assembly into the casement window utilise 13.71 MJ/kg. This represents in the region of 18 percent of total life-cycle energy consumption - nearly half of which is attributed to the carriage of the PVC-U profiles between *Profile extrusion* and *Assembly* operations sub-systems.

2.2 Transportation energy

The transportation distance attained during the eco-profile's life-cycle is in excess of 5400 km and provides a significant contribution to total life-cycle energy use. The carriage of low-mass materials increases total life-cycle transportation use to 11 per cent. As a consequence the delivery of profile lengths to the assembly site displays a four-fold increase in energy consumption over bulk transportation of polymer powder. Empty vehicles on return routes further add to the inefficiency of regional distribution.

3.0 DISCUSSION

The environmental impact of the eco-profile is primarily attributed to polymer formation, the transportation of extruded joinery profiles and the fuel feedstock mix associated with delivered electrical energy. Material waste generated in *Profile extrusion* and *Assembly operations* sub-systems further increase the life-cycle burden due to the cumulative impact on upstream operations. Increased efficiency in polymer formation over recent years [Krähling 1999:Boustead 1998] offers little opportunity to provide significant process energy savings. The machine processes involved in the *Profile extrusion* sub-system also offer limited scope for consistent energy savings due to the variabilities experienced in profile extrusion and associated downline calibration processes.

Enhancing the eco-profile of PVC-U joinery profiles within the UK may however be attained by exploring three considerations; delivered electrical energy efficiency, the re-use of virgin PVC-U waste generated and the transportation of goods between each sub-system.

Electrical energy efficiency is determined by primary fuel mix employed and the method of conversion. Delivered energy efficiency within the UK in 1998 was in the region of 34 per cent [DUKES 1999] due the continued reliance on coal feedstocks. Virgin PVC-U waste generated during the eco-profile's life-cycle has a cumulative impact in the region of 13 per cent. Existing enduse operations for the eco-profile result in the PVC-U waste being recycled into low-grade systems.

Moreover, the carriage of high volume joinery profiles and empty return transport account for two-thirds of total life-cycle transportation energy use. As a consequence improvement analysis of the eco-profile must target the interaction between material reuse, the use of existing logistics to return virgin waste and the increase in delivered electrical energy efficiency. As the Systems Model program may explore the previous considerations, the potential of reducing the cumulative life-cycle impact of 83.27 MJ/kg may be considered by optimising the transportation and re-use of material scrap.

4.0 MODELLING RE-USE OF PVC-U SCRAP

The System Model review sheet illustrated in Figure One identified the polymer waste generated during profile extrusion and assembly operations. Closed-loop recycling of the resultant virgin waste may be attained by the inclusion of a regranulation process. The developed model enables the potential gain of material reuse to be investigated. Table One identifies the primary impacts associated with the differing reuse scenarios. FU provides data on the completed eco-profile for the life-cycle of the four joinery profiles specific to the original study [Flanagan et al 1999].

Table One: Modelled PVC-U re-use scenarios

Scenario	Recyclate percentage	Process energy	Transportation energy	Total energy Use	Cumulative energy	Process CO_2	Transport CO_2	Total CO_2

	input	loss	(MJ/kg)	(MJ/kg)	(MJ/kg)	saving	(g/kg)	(g/kg)	(g/kg)
FU	-	-	73.69	9.58	83.27	-	1425	795	2220
1	5	5	70.37	9.22	79.59	4 %	1385	765	2150
2	5	10	67.26	12.27	79.53	5 %	1213	1039	2252
3	10	25	62.11	11.87	73.98	9 %	1224	1104	2328

4.1 Scenario One: Re-use of extrusion scrap

Scenario One identifies the reintroduction of five per cent "in-house" PVC-U waste generated during the extrusion of the FU profiles. The regranulation of virgin waste incurs its own energy use of 0.22 MJ/kg and experiences a five per cent recyclate loss from the system. The reintroduction of the recyclate provides a 3.32 MJ/kg reduction in cumulative energy consumption due to a decrease in upstream processing requirement and transportation. Carbon dioxide emissions reduce accordingly.

4.2 Scenario Two: Re-use of extrusion and assembly scrap

Scenario Two explores the life-cycle impact of further improving the previous preposition by returning assembly waste to the extrusion site via the existing transportation system in place. The System Model can subsequently examine the impact of processing a second "batch" assembly waste in addition to Scenario One extrusion waste use. Material reuse quantities are determined to be five per cent for both extrusion and assembly, against a respective five and ten per cent reuse sub-system process loss. Cumulative process energy reduces to 67.26 MJ/kg - a eight per cent process energy saving over the eco-profile. This saving is however offset by an increase in transportation energy due to the return of assembly waste to site.

4.3 Scenario Three: Re-use of extrusion, assembly and enduse scrap

Re-use scenario Two investigated the reintroduction of a maximum ten per cent recyclate as permitted in BS 7413 [1992]. Scenario Three examines the life-cycle impact of reprocessing enduse PVC-U joinery and employing a further ten per cent scrap. The total recyclate content is therefore in the region of 17 per cent, given a sub-system reprocessing loss of 25 per cent. The energy use associated with segregating the polymer from redundant joinery adopts a reprocessing energy use of 1.08 MJ/kg. This value reflects the process energy consumption of the VEKA automated reprocessing plant [IKP 1998]. The collection and delivery of the enduse recyclate also incurs a modelled transportation impact associated with the carriage of a three tonne load over 400km using rigid 14-17t diesel vehicle. A factor of 1.7 quantifies empty return.

The increase in material recyclate enables Scenario Three to record the greatest reduction in scenarios modelled. The nine per cent reduction in cumulative energy use over the eco-profile is primarily due to a significant reduction in virgin material required. *Raw Materials* and *Polymer Formation* sub-systems record a revised sub-system process energy use of 35.28 and 14.77 MJ/kg respectively (eco-profile values being 45.99 MJ/kg and 19.26 MJ/kg). Increased transport distance is offset by the reduction in the carriage of virgin polymer.

The carriage of low-weight recyclate however results in transportation emissions increasing by 15 per cent, whilst the additional electrical energy required by the *Re-use of virgin waste* sub-system further negates the savings associated with material reuse. Indeed as *Raw Materials* formation predominately utilises hydro energy, the opportunity to reduce emissions is restricted. Airborne emissions consequently increase, with total carbon dioxide value rising by three per cent

5.0 CONCLUSION

The FU embodied energy impact of 83.27 MJ/kg is primarily associated with the formation of the polymer compound and transportation impact during the life-cycle investigated. Material waste generated during profile extrusion and assembly increase the cumulative impact of polymer formation by a further 13 per cent. The System Model developed enables the complex interactions experienced between material re-use, transportation energy and resultant impact on upstream processes to be assessed. In turn program operation allows differing enduse scenarios to be investigated and therefore quantify the impact of material re-use and recycling. The reintroduction of ten per cent recyclate for example attains a net reduction of five per cent over the specific eco-profile. The reapplication of scrap material into new profile systems subsequently reduces the burdens associated with upstream polymer formation.

The re-use of both virgin and PVC-U waste can therefore provide a significant benefit on reducing the life-cycle impact of the polymer. Prognos [2000] concurs this consideration and accepts virgin scrap and post consumer wastes provide an environmental advantage where the polymer can be readily separated. Moreover, Weinlein's LCA into PVC-U joinery [1996] enforces this assertion by identifying the reintroduction of 70 per cent recyclate provides a recycled profile with life-cycle energy savings in the region of 50 per cent. As consequence environmental assessments conducted by Krähling [1999] conclude the ecological burden of the polymer becomes comparable with all other joinery systems when material recycling is adopted.

As true re-use and recycling remains concerned with saving energy and materials over the total life-cycle, the reapplication of PVC-U scrap in new systems therefore negates the burdens associated with polymer formation - the eco-profile's greatest sub-system impact. The values generated by the System Model enforce this consideration, with the reintroduction of ten per cent recyclate providing comparable life-cycle savings.

The environmental impact of PVC-U joinery can be subsequently reduced within existing performance controls by the co-ordination of sub-system processes associated with the material's life-cycle. However under current specification standards governing white PVC-U joinery profiles, a higher eco-profile saving of the eco-profile investigated cannot be reasonably provided due to the performance requirements of this study's joinery system precluding a higher recyclate content. A caveat to this consideration remains that substantial quantities of reworked polymer could be included without loss of performance should the FU follow a different mode of profile reuse, including for example coextrusion and foil coated systems.

The previous scenarios highlight the balance between material processing and energy use, with a rise in polymer reuse being offset against an increase in process and transportation energy. Energy use is subsequently proportional to recycling and forms a defined curve of environmental burden based on parameters that remain unique to each life-cycle.

The mechanical re-use and recycling of the material into high value products therefore reduces the ecological burden of its formation. Co-ordination of the infrastructure required for collection segregation and reprocessing negates life-cycle transportation burdens. The key of the polymer's continued specification and use as a joinery system consequently remains not with its formation and use - but that of its enduse.

References

Argus (2000) *"The behaviour of PVC in landfill"*. Final Report Feb 2000. European Commission DGXI.E.3.

Boustead I (1998) *"Eco-profiles of the European plastics industry". Polyvinyl chloride. Second Edition,* APME, Brussels.

BS7413 (1991) *"White PVCu extruded hollow profiles with heat welded corner joints for plastics windows: materials type A"*. BSI. London. ISBN 0-580-19372-1

DEFRA (2001) *"UK response to the European Comission's Green Paper on the environmental issues of PVC"*. Department of Environment, Food and Regional Affairs. July 2001. http://www.DEFRA.gov.uk/environment/waste/pvcresponse.

DUKES (1999) *"Digest of United Kingdom Energy Statistics 1999"*. Government Statistical Service. The Stationary Office, London. ISBN 011-5154639

Flanagan L, Miller AJ and Philip M (1999) *"Environmental impacts associated with PVCu joinery"*. COBRA 99: The challenge of change. Vol 1. 1999pp 274-283.RICS Publications. ISBN 0-85406-972-0.

IKP (1998). "*Integrated Life - cycle assessment of windows and curtain walls"*. Institute of polymer testing and polymer engineering, University of Stuttgart. Bockenhiemer Anlage 13, D-60322 Frankfurt.

ISO 14041 (1997) *"Illustrative examples on how to apply ISO 14041 -Life cycle assessment-Goal and Scope definition and inventory analysis"*. International Standards Organisation.

Krähling H (1999) *"Life cycle assessments of PVC products: Green guides to ecological sustainability"*. LCA Documents. Vol. 6 1999. Eco-Informa Press, Bayreuth, Germany. ISBN 3-928379-58-5.

Plinke E, Wenk N, Wolff G, Castiglione D and Palmark M (2000). *"Mechanical Recycling of PVC wastes"*. Study for DGXI of the European Commission. Final Report. B4-3040/98/000821/MAR/E3.

Prognos (2000). *"Mechanical Recycling of PVC wastes"*. Study for DGXI of the European Commission. Final Report. Plinke E, Wenk N, Wolff G, Castiglione D and Palmark MB4-3040/98/000821/MAR/E3.

Richter K. (1996) *"Compilation of a Life cycle inventory for wood, wood/aluminium and Plastic windows"*. Ed: Brandup, Bittner, Menges and Michaeli. Hanser Publishers. pp 160-167 . ISBN: 3-446-18258-6.

Weinlein R (1996) *"Vergleichende Umweltanalyse von Thermoplast- Bauteilen aus Recyclat und Neuware"*.Scriftenreine kunstoff – Forschung No 37, TU Berlin.