LIFE CYCLE OF WINDOW MATERIALS - A COMPARATIVE ASSESSMENT

M. Asif BSc MSc, **A. Davidson** BSc and **T.Muneer** PhD DSc CEng MImechE FICBSE Millennium Fellow

School of Engineering , Napier University, 10 Colinton Road, Edinburgh EH10 5DT, U.K.

ABSTRACT

This article addresses the life cycle assessment of the materials normally used for window frames, highlighting their respective benefits and weaknesses. Frames of different materials have been assessed on the basis of their production, energy consumption and environmental impacts. It has been found that the embodied energy of the windows made of aluminium, PVC, Al-clad timber and timber, for a reference window (1.2m×1.2m), are 6GJ, 2980MJ, 1460MJ and 995MJ respectively. The investigation shows that aluminium and PVC frames exhibit large amounts of environmental burdens. Accelerated ageing tests have been carried out to test the durability of windows against weathering impacts. These tests show that aluminium clad timber windows are comparatively least affected by environmental impacts. The article also provides results of a survey carried out with housing associations on performance of the studied windows.

1. INTRODUCTION

Windows play a significant role in buildings and are available in a wide range of designs and frame materials. The primary contribution of windows to buildings is to incorporate daylight and to maintain interior environment at desirable comfort conditions. An important aspect of windows is their environmental impact – energy consumption, natural resources depletion and environmental burden associated with their manufacture and service life. Windows are also expected to be durable and economical with the least possible cost to prospective owners.

This article gives a comparative analysis of window frame materials; aluminium, PVC, timber and aluminium-clad timber. A Life Cycle Assessment (LCA) approach has been adopted to evaluate these frame materials regarding their production taking into account the affiliated energy and environmental impacts. Results of any LCA study are always dictated by the defined goals, objectives and investigation boundaries of the framework. The results also depend upon the inventory analysis that is undertaken. For example, if energy consumption is considered, this may differ from country to country. A comparative embodied energy analysis for the windows presently discussed has been carried out for a reference window with dimensions of 1.2m×1.2m. This study also provides the findings of accelerated testing programme carried out to assess the weathering performance of materials. Comparative environmental impacts of the frame materials are also discussed, however, environmental impacts of painting/coatings on aluminium and timber, cleaning detergents for PVC, disposal of windows and their respective toxicity generation tendency are beyond the scope of this study. Similarly, packaging and transportation factors have also been excluded in this LCA study. The article also gives a review of a survey carried out with housing associations on performance of the windows presently examined.

2. WINDOW FRAME MATERIALS AND THEIR IMPACTS

2.1 Aluminium

Aluminium is produced from its abundantly available ore, bauxite. Primary, aluminium production requires a great deal of energy (225MJ/kg) (1) and it generates huge amounts of environmentally dangerous pollutants like carbon dioxide, acidic sulphur dioxide, along with polyaromatic hydrocarbons (PAHs) fluorine and dust (Table 1). Aluminium can be recycled repeatedly with virtually no deterioration in quality. Recycling aluminium requires only about 7% of the energy needed for primary aluminium production from its ore(2). Fig.1 shows the production of primary and secondary aluminium(3).

Aluminium windows are light and durable made of hollow extruded profiles assembled with mechanical fasteners. Because aluminium is highly heat conductive, a thermal break, usually made of plastic, is incorporated into the frame to reduce direct conductivity between the inside and outside parts of the window. This increases the temperature of the inside surface of the framing and somewhat reduces its potential for surface condensation(4). Fig.2 shows the LCA of aluminium windows.

Table 1. GWP and AP values for the European continent

Material	GWP	AP
Timber	116	1
PVC	1400	13
Aluminium	11102	60

GWP – Global warming potential in grams CO_2 equivalents
AP – Acid potential in grams SO_2 equivalents

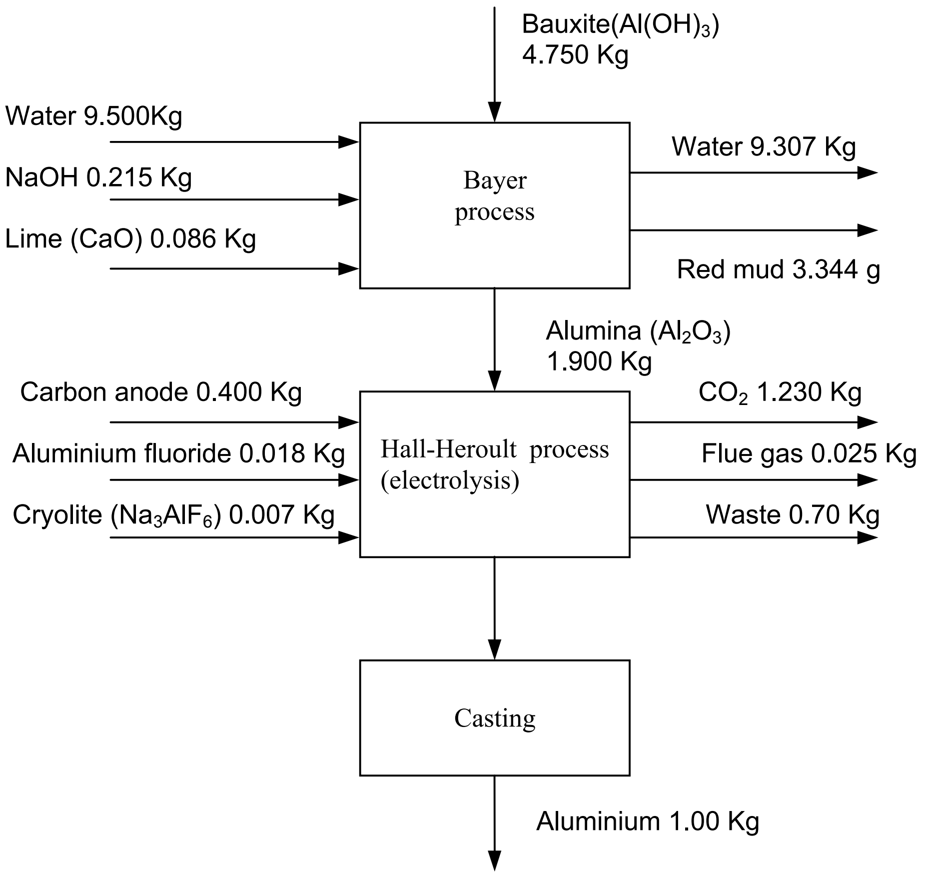

Fig.1(a). Primary aluminium production from raw material

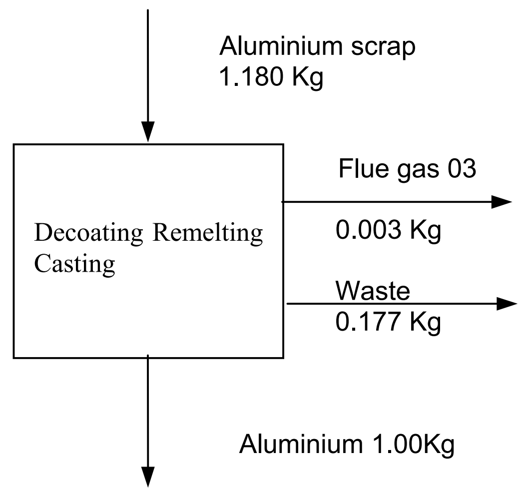

Fig.1(b). production of secondary aluminium

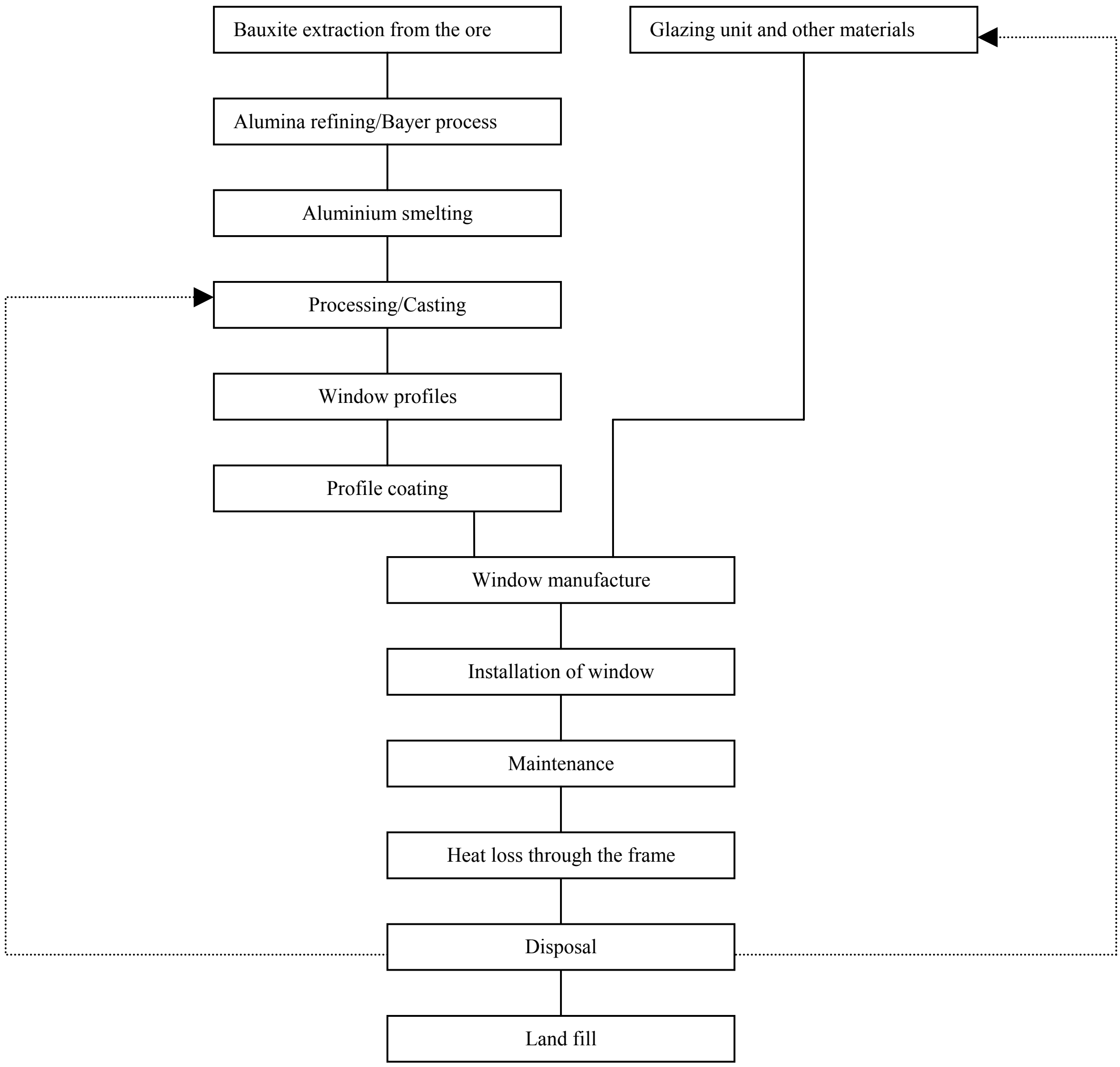

Fig.2 LCA of an aluminium window

2.2 PVC

Polyvinyl chloride (PVC) is a synthetic materials, made up of repeating units of vinyl chloride. PVC is comprised of chlorine, carbon, and hydrogen and its resin is 51% chlorine by weight. The remainder is hydrogen and carbon, which are derived from fossil fuels: primarily natural gas and petroleum. The production of PVC is also an energy-intensive process (70MJ/kg) (2,5) and produces many poisonous pollutants such as hydrocarbons, dioxins, vinyl chloride, phthalates and heavy metals required for processing as shown in Fig3 (6). PVC decomposes very slowly and as a waste product it contains environmentally dangerous substances that can seep out into soil and ground water(2). The recycling of PVC is a complex procedure due to the presence of associated polymers and reinforcements materials(7). Fig 4 shows the LCA of PVC windows.

The characteristics of PVC used in windows vary, since the additives play an important role in the properties of the end product and there have been many advances in material formulation(8). Additives can be plasticizers to reduce brittleness and improve processing, or stabilisers to protect against degradation caused by heat, oxidation and solar radiation.

A PVC frame is made of hollow profiles joined with heat, or solvent welded. PVC windows are also made with metal reinforcements to increase the rigidity; this tends to increase its overall thermal conductivity. PVC windows are stable in saline and polluted air, while they have high coefficient of thermal expansion (two to three times higher than aluminium)(4,9,10). PVC is very sensitive towards high temperature and ultraviolet (UV) radiation, which can break its molecular bonds, resulting in embrittlement and discoloration.

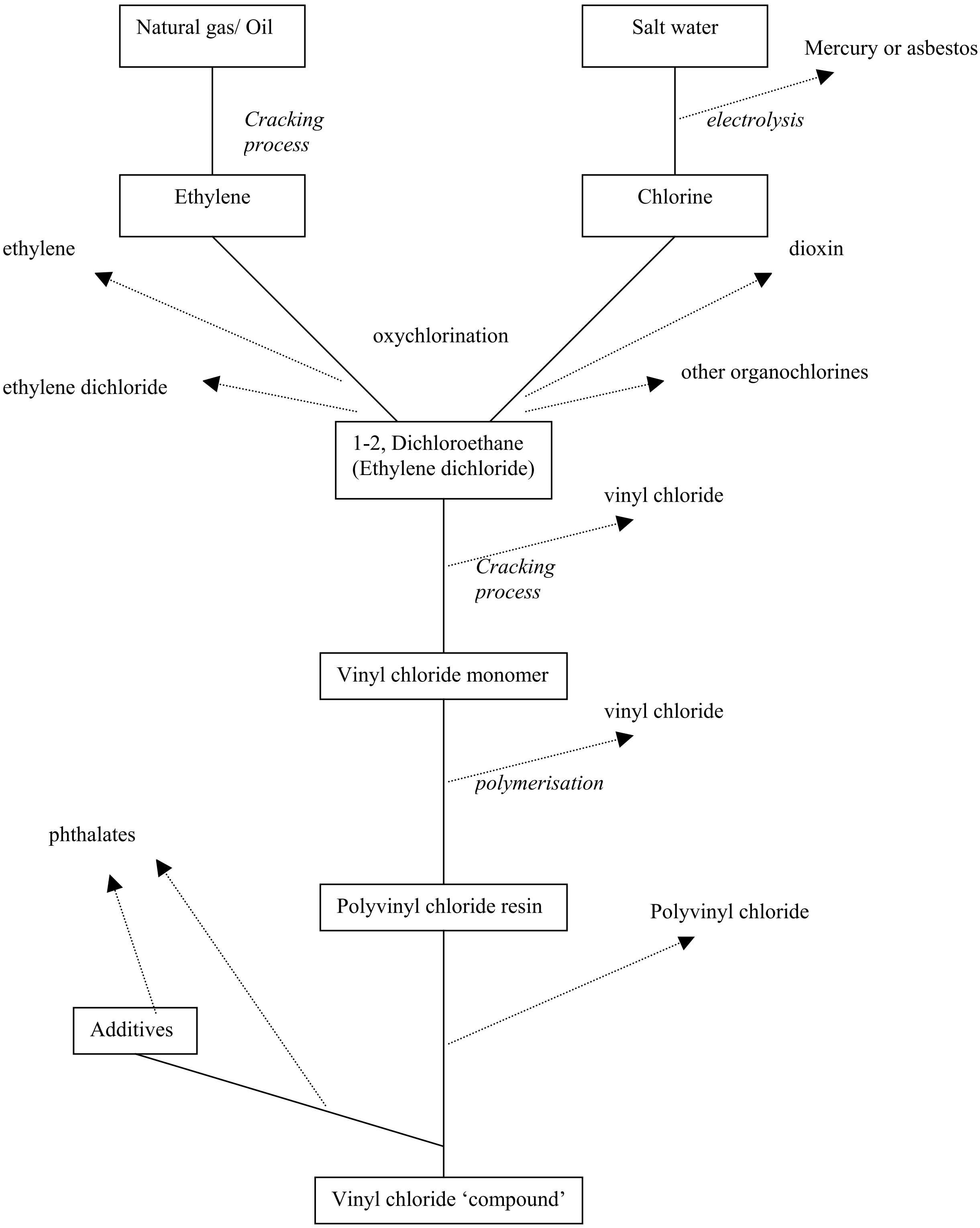

Fig.3 PVC production and associated emissions

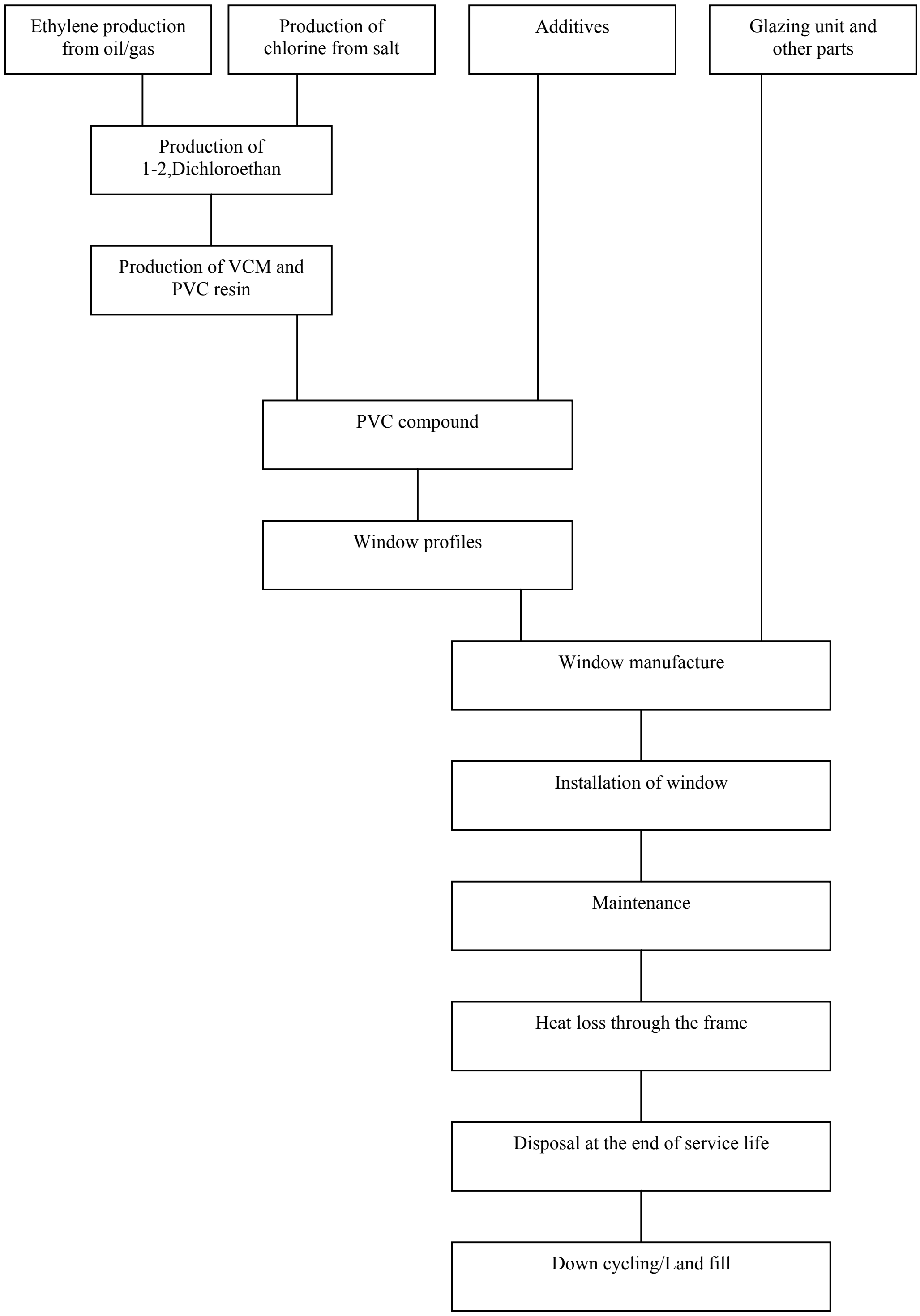

Fig. 4 LCA of a PVC window

2.3 Timber

Timber mainly consists of cellulose, lignin and other organic substances such as proteins, sugar, resin and water. Composition of these substances differs with the types of trees. Environmental concerns have led to the introduction of sustainable forest management. This ensures that for every tree that is felled, at least another two are planted, especially in Scandinavian forests (11). Timber therefore, can be defined as a renewable material with a very low embodied energy (5.2 MJ/kg) (12) as compared to Aluminium and PVC.

Timber is the traditional window frame material, because of its availability and ease of processing. Timber has the lowest thermal conductivity amongst frame materials(4). A variety of wood species are used for window frames like pine, cedar and redwood. Wood can be affected by moisture, which can make it warp or twist. Timber windows have to be painted or stained and must be maintained every few years. Fig.5 shows the LCA of timber windows.

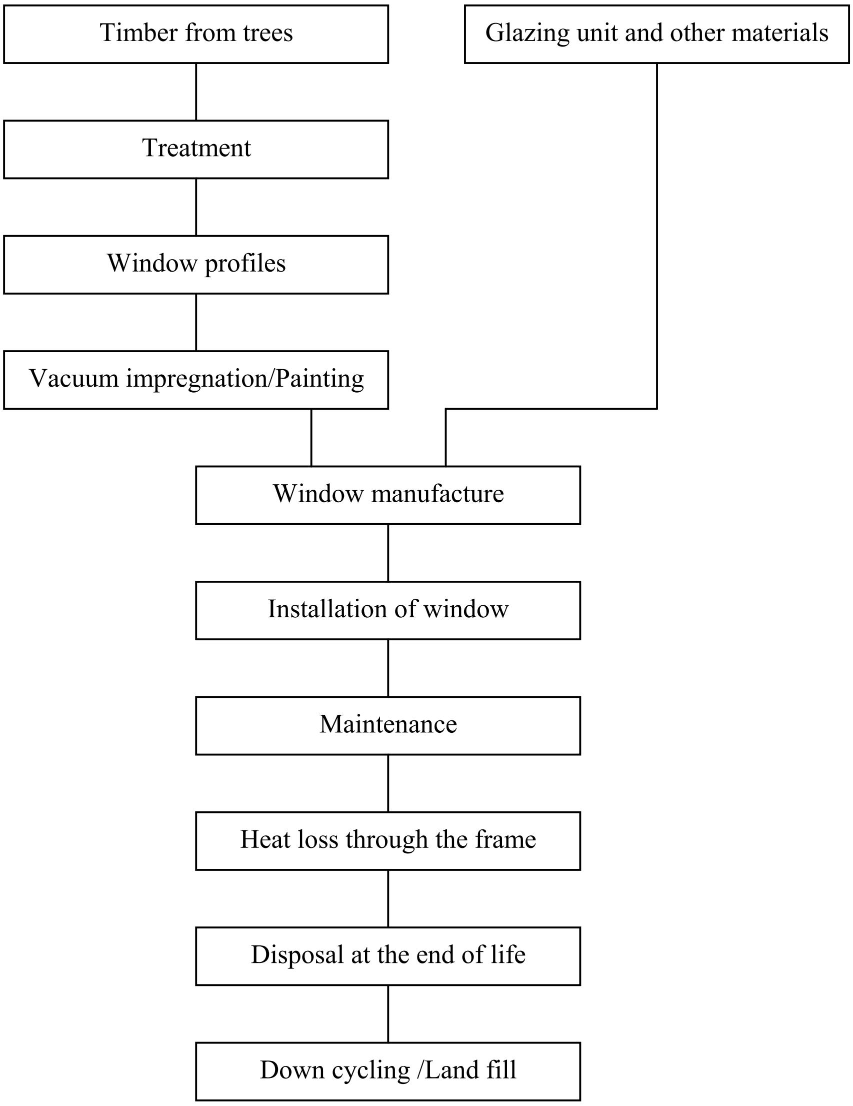

Fig. 5 LCA of a timber window

2.4 Al-clad timber

Timber windows are also made with aluminium cladding on the exterior face of the frame. Cladding aims to protect the timber underneath from weathering impacts. Aluminium profiles used for cladding are powder coated or anodised for protection against corrosive attacks. Clad frames require almost no external maintenance, while retaining the attractive wood finish on the interior. Fig.6 shows the LCA of aluminium-clad timber windows.

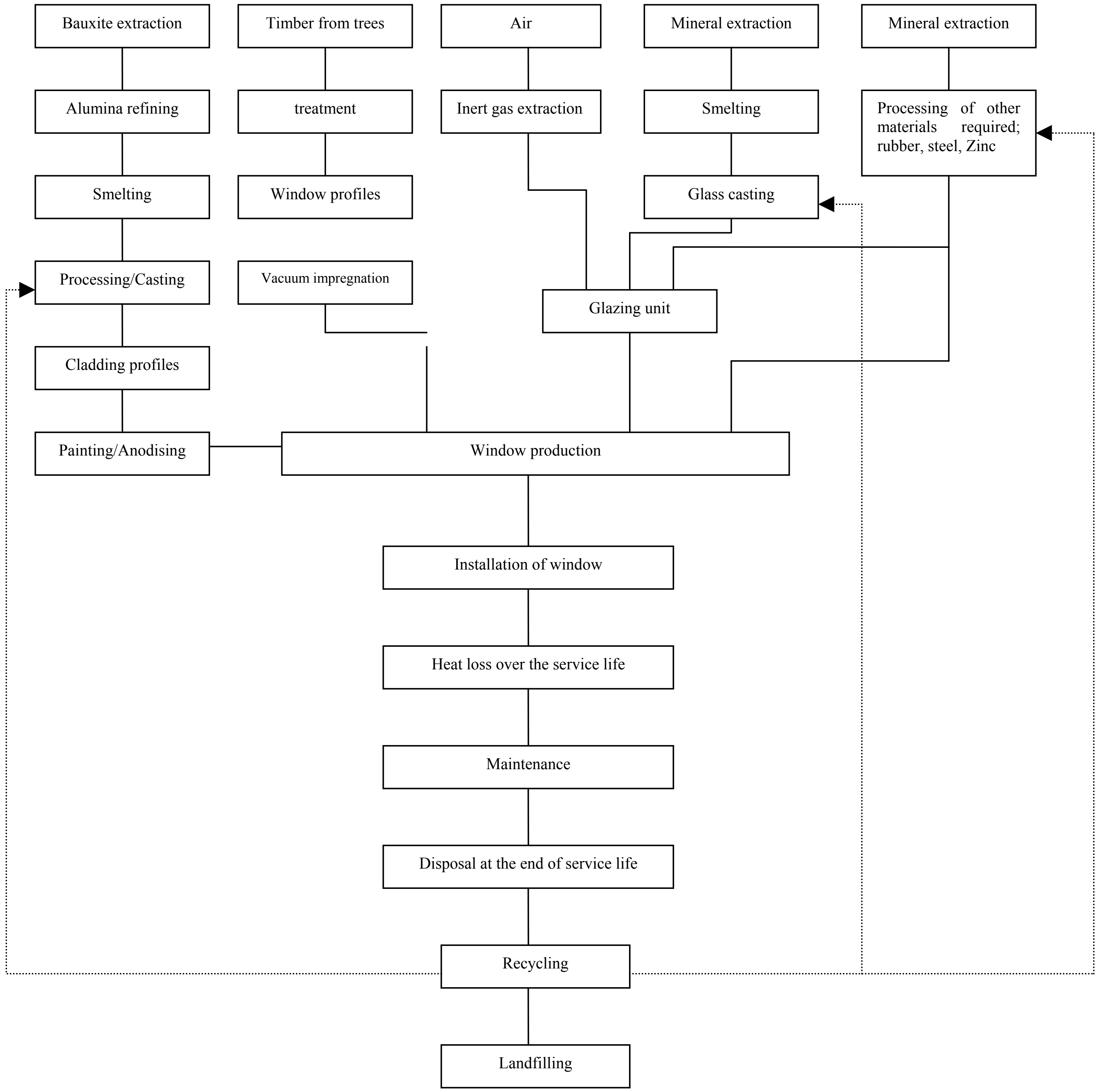

Fig.6 LCA of an Aluminium-clad timber

2.5 Embodied Energy Assessment

A standard window (1.2m × 1.2m) has been evaluated for its embodied energy with aluminium, PVC, Al-clad timber and timber manufacture. It has been found that the aluminium windows consume the highest amount of energy equal to 6GJ. PVC, Al-clad timber and timber windows have their respective embodied energy equal to 2980 MJ, 1460MJ and 995MJ as shown in Fig.7.

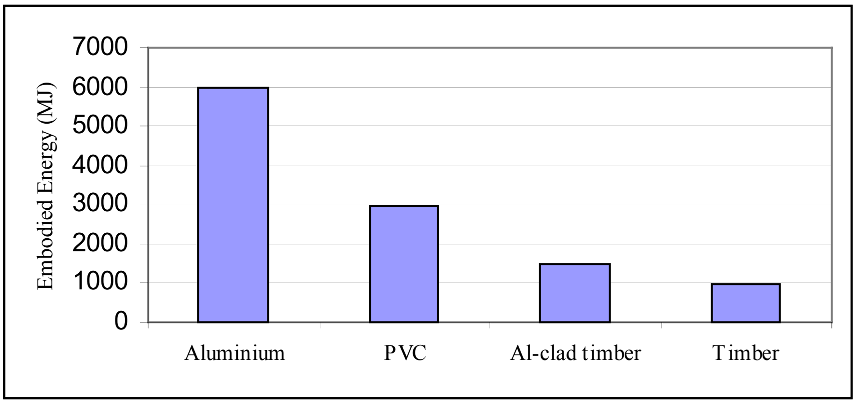

Fig. 7 Embodied energy of frames**

**energy contents differ depending upon production techniques adopted and resources of energy consumed, i.e. stated energy figures would be lower in Scandinavian peninsular

3 ASSESSMENT OF DURABILITY AND SERVICE LIFE OF FRAMES

3.1 Performance of windows - Survey Results

Windows in real-life undergo environmental conditions that cause gradual degradation to them. Real-life exposure of windows involve such varied factors as geometric configuration and details of the construction, composition, porosity, and adherence of corrosion products, environmental pollution, humidity, sun exposure and temperature variations.

Besides the choice of material, proper maintenance and cleaning is another important factor in durability and service life of windows. It has also to be considered that the service life of windows is not only a quantifiable technical property, but there is also an aesthetic and fashion input to it; life of windows therefore, depends upon economical, functional, social and physical performance. A survey has been carried out with the help of local authorities throughout UK, to investigate the performance of studied windows in real life. The survey consisted of a questionnaire in which authorities were asked about effective service life and maintenance characteristics of windows. Survey feedback, received from 22 authorities, has been summarised in table 2. Survey results have shown significant variation in the perception of service life of both PVC and timber windows. Aluminium and al-clad timber windows, however, have been consistently reported to be durable and long life.

Table 2 Survey analysis results

Window (frame type)	*Estimated service life*			*Characteristics*
	Mean	Median	Inter-quartile range	
Aluminium	43.6	40	12.5	Low maintenance
PVC	24.1	22.5	15	Low maintenance, difficult to repair
Timber	39.6	35	16.3	High maintenance, easy to repair
Al-clad Timber	46.7	45	10	Low maintenance, easy to repair

3.2 Accelerated ageing

An accelerated testing programme has been carried out to compare the performance of frame materials against weathering and environmental impacts. Since every material has its own degradation parameters, the environmental factors affecting the materials, and the intensity of these degradation factors, differ from material to material. For example, timber and PVC can undergo biological attacks but aluminium has no such threats. Therefore, some of the tests carried out were for all materials simultaneously to assess their comparative performance to common degradation factors, while the rest of the tests were focussed on individual materials to assess their performance under particular conditions. Table 3 shows a summary of tests carried out.

Table3 Summary of accelerated tests

Test	*Samples tested**	*Test conditions*
Immersion	Uncoated & coated aluminium	Immersion in a solution of 0.14M HCl and 0.26M NaCl - 24 hours
Dry-wet cyclic	Uncoated & coated aluminium, timber, PVC and Aluminium-clad timber	Cycle consisting of 2 min of water spray, 15 min of UV light and 3 min of heating at 55C – 96 hours
Slat spray	Uncoated & coated aluminium, timber, PVC and Aluminium-clad timber	5% NaCl mixture – 96 hours
Humidity/temperature	Uncoated & coated aluminium, timber, PVC and Aluminium-clad timber, complete window units of timber, PVC and Al-clad timber	24 h at 60°C and 88% relative humidity followed by 24h at 60°C heating-144 hours
Ultra violet	Uncoated & coated aluminium, timber, PVC and Aluminium-clad timber	alternating cycles of 4 hours of exposure to UV-lamps at 45 °C and 4 hours of condensation at 50°C - 2 weeks.

* Samples of aluminium windows tested were 6061 alloys. Timber samples were extracted from different softwood made windows while PVC samples were obtained from windows of unknown composition. Note that PVC is manufactured in a wide range of compositions whose specifications are not readily available.

3.3 Results of the tests

Samples tested included complete units of small sized windows as well as small pieces, 5 cm by 5 cm, of frame materials depending upon the limitations of the testing chambers. After the tests, samples were investigated visually and using optical and atomic force microscopy. Findings from these tests are summarised below.

- Uncoated aluminium samples exhibited corrosive effects under humid and high temperature conditions (Fig.8). Powder coated and anodised samples remained unaffected.
- Small timber samples exhibited warping and crevice-opening effects upon exposure to moisture and temperature (Fig.9). However complete timber window units and other sample that had received proper surface treatments revealed no such flaws. UV testing resulted in little discoloration of timber samples.
- PVC samples remained unaffected under humid conditions; however, PVC deteriorated significantly as a result of temperature/humidity and UV tests. The latter test resulted in severe discoloration(F10).
- Aluminium clad timber samples did not receive any deteriorating impacts under any of these conditions as aluminium itself remained uncorroded due to its coating layers and it kept the wood underneath protected from adverse conditions.

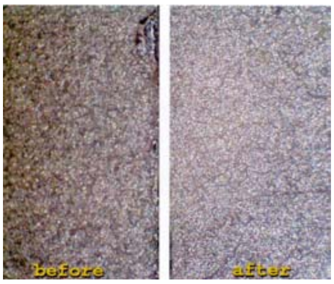

Fig.8 Uncoated aluminium sample before (left) and after (right) immersion test

Fig. 9 Crevice opening in timber sample after cyclic test

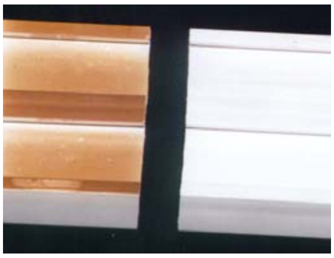

Fig. 10 PVC sample before(right) and after (left) UV test

4. ECONOMIC ASPECTS

There is no standard procedure to compare the capital cost of frames of different materials due to a number of factors including the quality and functionality of windows, brand names and marketing strategies such as, discounts and incentives.

In terms of maintenance cost, timber windows are the most expensive as they require regular maintenance of the frame i.e. painting or staining after every 5 years. Aluminium frames need only to be cleaned to maintain their bright appearance (13). PVC frames should be cleaned with alkaline detergents after every 6 months to maintain their appearance(14). Al-clad frames require no external maintenance since the coating keeps the cladding protected against environmental impacts. Underneath the cladding a well treated timber should not require any maintenance since it is not exposed to environmental degradation.

Another economic aspect of windows is their running cost - primarily the energy cost in the form of heat loss through them, particularly in cold climates. Aluminium windows have very low thermal resistance (high U-value) unless provided with thermal breaks. Timber and PVC windows have good thermal resistance while al-clad windows exhibit the same thermal properties that of timber ones.

5. CONCLUSIONS

- Aluminium frames cause the highest burden to the environment because of the dangerous pollutants release and high energy consumption during aluminium production. PVC contributes large amounts of poisonous pollutants throughout its life cycle, while timber window frames have the least environmental burdens.

- Embodied energy analysis has been carried out for a standard 1.2m $\times$ 1.2m window. Aluminium windows have the highest embodied energy, amounting to 6GJ. PVC, Al-clad timber and timber windows have embodied energy of 2980MJ, 1460MJ and 995MJ respectively.

- All frame materials deteriorate to various degrees by environmental impacts. PVC is sensitive towards heat and UV radiation. Timber if not frequently treated, can easily be affected by environment. Aluminium, if not protected well by coatings, gets damaged under corrosive conditions especially in coastal and industrial areas. Al-clad frames are unlikely to deteriorate due to their protective coatings and appear to be the best choice from this point of view.

- A survey analysis shows that aluminium and timber windows can easily last more than 40 years. Al-clad timber being new on the market, is expected to have a service life well over 40 years. PVC windows, in most cases, are reported to have an optimum service life of 25 years.

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