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Life cycle assessment of aluminium-clad timber windows

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PhD

Napier University
Edinburgh

2002

DECLARATION

I hereby declare that the work presented in this thesis was solely carried out by myself at Napier University, Edinburgh, except where due acknowledgement is made, and that it has not been submitted for any other degree.

Muhammad Asif

Date

ABSTRACT

Over the last century a temperature rise of 0.6 C in global climate and the affiliated greenhouse effects have inflicted enormous impacts in the form of natural catastrophes, economical losses, health problems and seasonal disorder. If human activities continue at existing pace, a further temperature rise of 2 5 C is being anticipated over the next hundred years, which may cause unimaginable damage to humanity and ecology of the planet. In such a prevailing global environmental scenario sustainability is the need of hour and should be given the prime importance in execution of activities in all sectors in order to keep future secure for coming generations.

Windows are amongst the most sensitive elements in a building envelope, also, due to their multi disciplinary role, they are important not only for their effects on interior environment but also for the energy performance of the building. Energy contents and environmental impacts of the materials involved, add up on to window significance in the ecology of buildings. Energy efficient windows with least possible environmental burden over their whole life cycle are thus very important in achieving desired levels of sustainability in general, particularly in buildings.

The present work addresses the sustainability of double glazed aluminium clad timber windows adopting the life cycle assessment (LCA) approach. LCA of windows helps cutting down the associated ecological burdens at all stages, i.e. extraction/production of materials, operation, maintenance and disposal of windows at the end of their service life. Cost effectiveness and productivity, the important features of sustainability, have been evaluated for aluminium clad timber and timber windows on the basis of life cycle cost assessment (LCCA) approach. Value engineering (VE) of aluminium clad timber windows has also been addressed. Running and/or maintenance costs which largely determine the life cycle costing have been estimated and the most cost effective options are presented.

Four different types of windows, made of aluminium, aluminium clad timber, PVC and timber frame, have also been compared with respect to the ecology of frame materials - covering energy contents and environmental loads, maintenance and durability, service life and costing. A survey has been carried out with the help of housing authorities, architects and surveyors within UK, to study the performance of these windows in real life. A series of accelerated tests have been carried out to study the weathering performance of the candidate windows. The results have revealed that aluminium clad timber windows have excellent resistance against weathering conditions and they perform better than aluminium, PVC and timber windows under any conditions. In an ongoing research project at Napier, copper (Cu) coated silicon carbide (SiC) reinforcement particles have been used in aluminium 6061 matrix to enhance the mechanical properties of the Al SiC metal matrix composite (MMC), which is a prospective material to be used in window hardware. Results have indicated that Cu coating does not bring any additional corrosion loads onto the MMC. Recommendations for further work have also been laid out.

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First of all I am thankful to God, Allah, who provided me with the strength, knowledge, and determination to achieve this goal.

I would like to thank my supervisory team, Alan Davidson, Tariq Muneer and Jorge Kubie for their continuous support and encouragement throughout this project. The confidence and trust they have had in me and my work, has helped me moving forward for which I am most grateful. The provision of insight and understanding of the research work by them, has been very important in my success, besides their generous guidance. It has been a worth enjoying experience working with them all, being a member of such an enthusiastic research team. Thanks also go to Gillian Weir for her time to time advice in the capacity of industrial supervisor.

At this moment I can not forget to thank my office colleagues, Tom, Ana and Colin, for their general guidance and advice. Thank you all, also, Xiodong, Imtithal, Fatema and Stewart, for developing such a supportive and friendly atmosphere in the research group. Thanks also goes to Bill Brownlee for his valuable help down in the lab.

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In the end my sincere and cordial well wishes to all mentioned above, for their success in respective careers and life ahead, wish you best of luck.

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NOMENCLATURE

Al	Aluminium
BRE	Building research establishment
ES	Earth Summit
E&EM	Energy and Environmental management
ISO	International standards organisation
LCA	Life cycle assessment
LCCA	Life cycle cost assessment
GWP	Global warming potential
GDP	Gross domestic product
MMC	Metal matrix composite
PVC	Polyvinyl chloride
SHGC	Solar heat gain coefficient
SiC	Silicon carbide
UV	Ultra-violet radiation
VE	Value engineering

I INTRODUCTION

1.1 INTRODUCTION TO GLOBAL ENVIRONMENTAL SCENARIO

Concerns about local and global environmental situation are rising in the developed and developing world. Global warming, ozone depletion, destruction of natural habitats, and loss of biodiversity are the cause of much debate in international forums. Global warming, and its various potential effects on the earth, is a consequence of a long term accumulation of the so-called greenhouse gases (CO_2 CH_4, NO_2 etc) in the higher layer of atmosphere. The emission of these gases is the result of intensive human activities such as the burning of fossil fuels, deforestation, land-use changes, etc (BSEE , 2001). The International Panel for Climate Change has determined that the world is definitely getting warmer. The global climate has experienced a temperature rise of 0.6°C in the last century. In England, the 1990s experienced four out of the five warmest years in a 340-year record, with 1999 being the warmest year ever recorded. The U.S. Environmental Protection Agency (EPA), in a report has indicated that by the year 2100, the global climate temperature is expected to rise between 2-5°C depending upon sustainability measures adopted over the coming years (Lashof et al 1991 as reported by Dincer, 1999). Global warming and its affiliated changes in the world's climate would have enormous consequences for people, economies and the environment. Many projections of the world's future climate show more intense rainfalls or snow storms, which are likely to lead to large-scale flooding of many locations. Between the 1960s and the 1990s, the number of significant natural catastrophes such as floods and storms rose nine-fold, and the associated economic losses rose by a factor of nine. Data on flood related monetary loss is presented in Fig. 1.1(Muneer et al 2003).

1.2 ENERGY, ENVIRONMENT AND SUSTAINABILITY

World population is expected to double by the middle of the 21st century (Dincer et al 1999). Global demand for primary energy consumption is seen to be rising even more rapidly. For the world as a whole, it can be seen that electricity consumption is expected almost to double by the year 2020. The expected future demand for electricity distributed by regions is demonstrated in Table 1.1 (Muneer et al 2000). It is therefore, clear, that if the energy needs of the planet's rapidly increasing population are to be met without irreparable environmental damage, there will have to be a world wide drive to conserve energy and improve the efficiency of its use. Sustainability approach has to be adopted to meet all energy needs for the foreseeable future, cleanly, safely and economically.

Materials are normally found in nature in impure form, e.g. in ores. Extraction or purification of materials from their natural ores is an involved activity that not only consumes energy but also results into waste generation. The waste may sometimes be enormous as highlighted in Fig. 1.2 that shows an ecological rucksacks of various materials. There is also an intimate connection between energy, environment and sustainable development. A society seeking sustainable development ideally must utilise only energy resources which cause no environmental impact (e g. which release no emissions to the environment). However, since all energy resources lead to some (not all) of the concerns regarding the limitations imposed in sustainable development by environmental emissions, their negative impacts can be in part overcome through increased energy efficiency. A strong relation exists between energy efficiency and environmental impact, since for the same services or products, less resources utilisation and pollution is normally associated with increased energy efficiency (Dincer et al 1999).

Sustainability has been defined as,

' *a development or practice which does not reduce the long-run productivity of the natural resource assets on which a country's income and development depend'*(Anderson, 2002).

UK government has defined sustainability as

'*development that meets the needs of the present without compromising the ability of future generations to meet their own needs'* (Anderson, 2002).

The focal point of the Earth Summit 2002, held in Johannesburg in September 2002, was sustainable development. In its plan of implementation, the summit urges every country especially the developed countries to take lead in adopting sustainability policies, stating;

All countries should take action, with developed countries taking the lead; encourage and promote the development of a 10-year framework of programmes in support of regional and national initiatives to accelerate the shift towards sustainable consumption and production to promote social and economic development within the carrying capacity of ecosystems by addressing and, where appropriate delinking economic growth and environmental degradation through improving efficiency and sustainability in the use of resources and production processes, and reducing resources degradation, pollution and waste (ES-2002).

1.3 SUSTAINABILITY AND CONSTRUCTION INDUSTRY

The construction industry, representing about 85 o of GDP, has a vital place in reducing the burdens on the planet's resources. Both in terms of new-build and the significant repair-and maintenance market, construction without depletion should be the aim. It is required to minimise resource use to ensure that the dwindling natural resources (fossil fuels, stone for aggregate, potable water etc) will last longer and go further. Also, the procurement of construction projects has a significant impact on the environment. The initial impact of a building on the environment results from the energy and other products consumed in its construction. Thereafter, the building continues to affect the environment directly and indirectly throughout its operation, maintenance, refurbishment and final demolition. Table 1.2 shows the main determinants of environmental impacts, both indoor and outdoors, associated with buildings, as highlighted by Reijnders (1999)

Agenda 21, the Rio Declaration on Environment and Development at the United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro, Brazil, 3 to 14 June 1992 emphasises the importance of sustainable construction, stating:

All countries, as appropriate and in accordance with national plans, objectives and priorities should;

Promote the free exchange of information on the entire range of environmental and health aspects of construction, including the development and dissemination of databases on the adverse environmental effects of building materials through the collaborative efforts of the private and public sectors;

and also to,

Promote the development and dissemination of databases on the adverse environmental and health effects of building materials and introduce legislation and financial incentives to promote recycling of energy-intensive materials in the construction industry and conservation of waste energy in building-materials production methods (UNCED-1992).

Because of the substantial environmental impacts involved, many industrialised countries have, in recent years, seen activities directed at environmental improvement of the building process, the use of buildings and deconstruction. Such activities are largely different between countries. This is understandable to the extent that building construction is often strongly determined by local traditions, local climatology and available natural resources. Moreover environmental impacts of similar production processes involved in building may vary strongly between countries. Whereas, for example, electricity used in different countries is produced from different resources, nuclear, hydropower etc that leads to diverging environmental impacts.

1.4 WINDOWS AND SUSTAINABILITY

A window is a multi dimensional and very influential element in a building. The basic parts of a window are the glazing, the sash, the frame, the sealants, weatherstrippings and the hardware (ironmongery). Quantitatively a window is defined by its visible transmittance, solar heat gain coefficient (SHGC), U-value and air leakage rate. In addition to its main function, visibility, a window should;

- control heat flow
- control air flow

- control water vapour flow
- control condensation
- control rain and snow penetration
- control solar and other radiation
- control sound transmission
- prevent the entry of insects
- control fire propagation
- be usable as fire exits all year long
- prevent forced entry
- be easy to operate by all groups of users
- provide strength and rigidity to the structure
- maintain satisfactory performance over service life
- be appealing and harmonious with the surroundings
- be economical

Windows have a direct impact on the energy efficiency of buildings. The improved characteristics of advanced windows can lead to substantial energy saving as a direct result of their use.

1.5 SCOPE OF PRESENT RESEARCH PROJECT

According to a survey carried out by the World Economic Forum, UK stands 98th in the world for a self defined Environmental Sustainability Index of indicators. Figure 1.3 presents a sustainability comparison of European countries in which UK holds the bottom ranking (E&EM, 2002). There is thus a need for adopting energy efficient and environmentally friendly activities in all sectors including the construction industry. Multi-disciplinary role of windows greatly influences the performance of buildings. Windows, with increased energy performance and ecologically better materials employed, can significantly help towards sustainability of buildings.

This work addresses the sustainability aspects of aluminium clad timber windows, adopting life cycle assessment (LCA) approach. LCA is a very helpful tool in this regard, as also highlighted by the 'Earth Summit 2002', which, in its plan of action, has urged the world to,

Develop production and consumption policies to improve the products and services provided, while reducing environmental and health impacts, where appropriate, science based approaches, such as life cycle analysis (ES 2002).

Agenda 21, on similar lines, states that all countries should;

Adopt standards and other regulatory measures which promote the increased use of energy efficient designs and technologies and sustainable utilisation of natural resources in an economically and environmentally appropriate way (UNCED-1992).

For windows, LCA approach can significantly help in cutting down the associated environmental burdens; affiliated with the production/extraction of materials involved, maintenance and disposal of windows at the end of their service life. Present work has aimed to investigate the energy and environmental impacts of aluminium clad timber windows. Cost effectiveness and productivity, important features of sustainability, were also aimed to be investigated on the basis of life cycle cost assessment (LCCA) value engineering (VE) approach. A comparison of aluminium clad timber windows with other window types (made of aluminium, PVC and timber) was also an objective of this work.

The defined research objectives were as follows:

- Energy and environmental impact assessment of aluminium clad timber windows
- Study of weathering performance of different windows (especially the aluminium clad timber windows) through accelerated testing
- Estimation of service life of windows
- Life cycle cost analysis (LCCA) & value engineering (VE) of aluminium clad timber windows
- Comparison of aluminium clad timber windows with other window types (aluminium, PVC and timber make) with respect to energy and environmental impacts, durability and service life, maintenance and repair, functional performance and price
- Investigation of the corrosion performance characteristics of Al-SiC (Cu coated) MMC that can be a prospective material to be used in window hardware.

Life cycle assessment of windows, has not been a much explored area for research activities especially from the frames perspectives. There have been a few LCA studies carried out on aluminium, PVC and timber made windows. Aluminium clad timber windows are the least explored window design. Being an effective member of window family, al-clad timber windows are important to be evaluated in terms of their performance, advantages and disadvantages, and potential ecological impacts. Further, the fact that all LCA studies set their own goals, boundaries and depths of investigation distinguishes them from each other. For example, Citherlet et al (2000), Weir et al (1998) and Lawson (1995) have worked on LCA of windows in recent years. Citherlet has focussed on the ecology of aluminium, PVC and timber windows providing their respective global warming potential (GWP) values and service life estimation. The latter study also provides the thermal performance of these windows, however, energy evaluation of window (embodied energy) itself has not been addressed. Weir has investigated the embodied energy of timber windows and discussed the environmental impacts of window elements such as timber, glass and infill gases. Lawson has compared the embodied energy of aluminium, PVC and timber windows and has derived the potential environmental impacts of these windows from their respective energy consumption. It is therefore obvious that LCA studies are driven by their set goals and limitations of their investigation. Present work provides a comprehensive life cycle assessment of aluminium clad timber windows encompassing not only on their energy and material balance along with affiliated environmental loads, but also highlights other aspects such weathering performance, service life and cost effectiveness.

The real significance of this work lies in its innovative approach on several issues. Life cycle cost analysis, for example, has been carried out to investigate the cost effectiveness of windows over their service life. Investigation of the environmental impacts on windows is a special feature of this work, for which artificial weathering of windows has been carried out through accelerated tests. The comprehensive comparison of four different windows on various fronts highlighting their respective advantages and disadvantages, is another special characteristic of this work. This work is therefore an addition on the ecology and performance of the studied windows especially the aluminium clad timber design. The results and findings of this work shall provide guidelines towards adopting sustainability approach in terms of windows construction and use - which would ultimately effect the performance of the entire building.

1.6 METHODOLOGY OF THE PRESENT PROJECT

An energy and environmental impact assessment, that is the core of any LCA study, was carried out for aluminium clad timber windows. Window and powder coating production units were visited in Norway to gather the data and other relevant information. Details were gathered through direct observation and assessment of entities, study of audit reports records available and interviews with relevant personnel at various stages of the projects. The work includes a detailed audit of the total energy consumption, that is, the energy involved in extraction/production of window parts and in processes involved in window manufacturing. Embodied energy of double glazed aluminium clad timber windows with different infill gases (Argon, Krypton and Xenon) have been obtained. Environmental burdens associated at different production stages have also been identified and estimated.

Windows, like all other materials and products, deteriorate with the passage of time, due to environmental factors and the conditions they are exposed to during their use. Environmental conditions such as ultra violet (UV) radiation, humidity, temperature and pollution, affect the durability and performance of windows. Weathering performance of windows, in its general sense (through normal usage) is a long and continuous process. In the present work, accelerated ageing tests were decided to be carried out to simulate various environmental conditions, so as to study the weathering impacts on windows in a short period of time. An accelerated testing programme was designed and executed both at Napier University and Otto-Von Guericke University in Germany. The methodology and experimental features of the tests carried out, have been discussed in detail in chapter 3. Respective protective measures have also been highlighted for the above mentioned window frames.

Service life asse sment provides valuable information in any LCA study. Service life estimation is a complex phenomenon since, there are a number of factors that could become decisive (individually or collectively) in obsolescence of windows. Service life of windows however, effe tively depends on the quality of materials employed, exposure conditions and maintenance. To estimate the performance and service life of windows in real life, a survey has been carried out with the help of local housing authorities, surveyors and architects within UK. Results of the survey have provided an estimate of the approximate service life of windows.

Life cycle cost analysis (LCCA) is an important feature in window's life cycle assessment. LCCA provides an economic assessment of a product over its entire service life. For windows, it is very important to evaluate not only their capital cost but also, their running cost in terms of maintenance expenses. LCCA has been carried out for aluminium clad timber and unclad timber windows with 6 different glazing compositions. As highlighted in chapter 5, energy cost is one of the most effective elements in the economic evaluation of windows. Energy cost varies significantly from place to place depending on the intensity of local climatic conditions. This analysis therefore, covers five different locations, London, Wales, Manchester, Edinburgh and Aberdeen. LCCA provides valuable information on economic usage of windows over the length of time. Service life of windows may also be identified in terms of its economical usage. LCCA therefore, also helps in determining the appropriate service life of windows.

Windows are available in a range of frame materials. Aluminium clad timber framed windows have been compared with those of other frame materials such as aluminium, PVC and timber. These window frames have been assessed on following basis:

- Energy and environmental impacts during production/extraction of frame materials and disposal of frames
- Durability and service life of frames
- Maintenance and repair
- Functional performance
- Price comparison and market scenario

Results of the above mentioned survey and the work done on other aspects such as energy and environmental impacts assessment, weathering performance evaluation through accelerated testing and life cycle cost assessment, also provided valuable input in carrying out this comparative as essment of frame materials.

1.7 WORK ON METAL MATRIX COMPOSITES (MMCs)

Metal matrix composites (MMCs) are materials with improved mechanical properties than usual monolithic alloys. MMCs have found wide range of applications in automotive, space, electronic, construction and leisure industries. In an ongoing research project at Napier, copper (Cu) coated silicon carbide (SiC) reinforcement particles had been used in aluminium 6061 matrix to enhance the mechanical properties of the Al-SiC metal matrix composite. Al-SiC MMC can be a prospective material to be used in window hardware due to its better mechanical properties. The already planned accelerated testing programme for windows and work done on corrosion of aluminium, were extended/applied to investigate the impacts of Cu coating on corrosion behaviour of this particular composite. Al-SiC MMC has been produced with and without Cu coating on the SiC. Samples were tested in three different tests carried out at Otto-Von-Guericke University in Germany, and results of these tests have been presented in chapter 7.

1.8 THESIS STRUCTURE

Literature review in any research work has its significance in terms of providing a wide spectrum of knowledge in the work area to build sound ground for the research work to be carried out, introducing the readers with the past as well as contemporary research efforts on similar lines. A great deal of literature review was carried out in this project. Due to the diverse nature of the project, background study carried out extends on a number of different fronts. In the presented thesis, unlike the common practice, an introduction of the literature reviewed, has not been provided as a single unit, it is rather distributed through chapters (2-7), that contain, where appropriate, the relevant literature.

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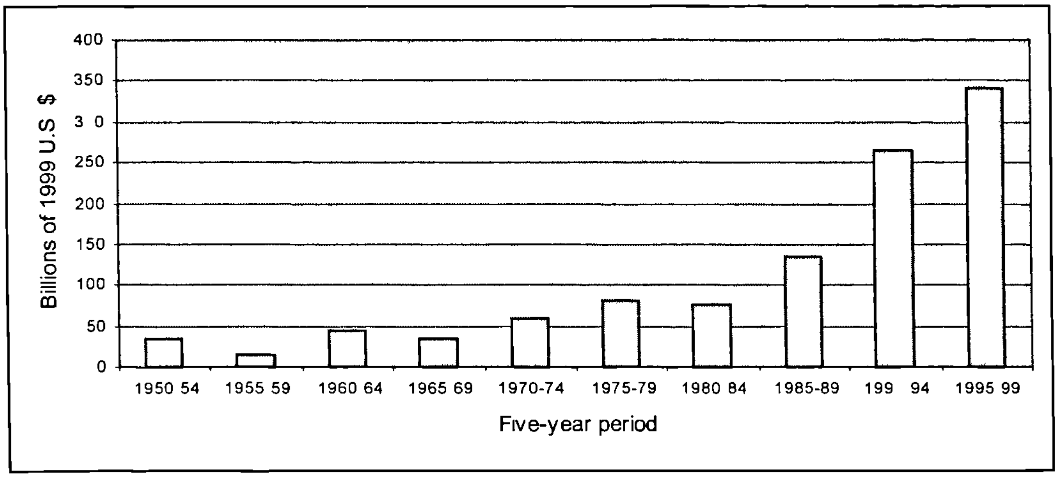

Fig. 1.1 Global direct economic losses from natural catastrophes

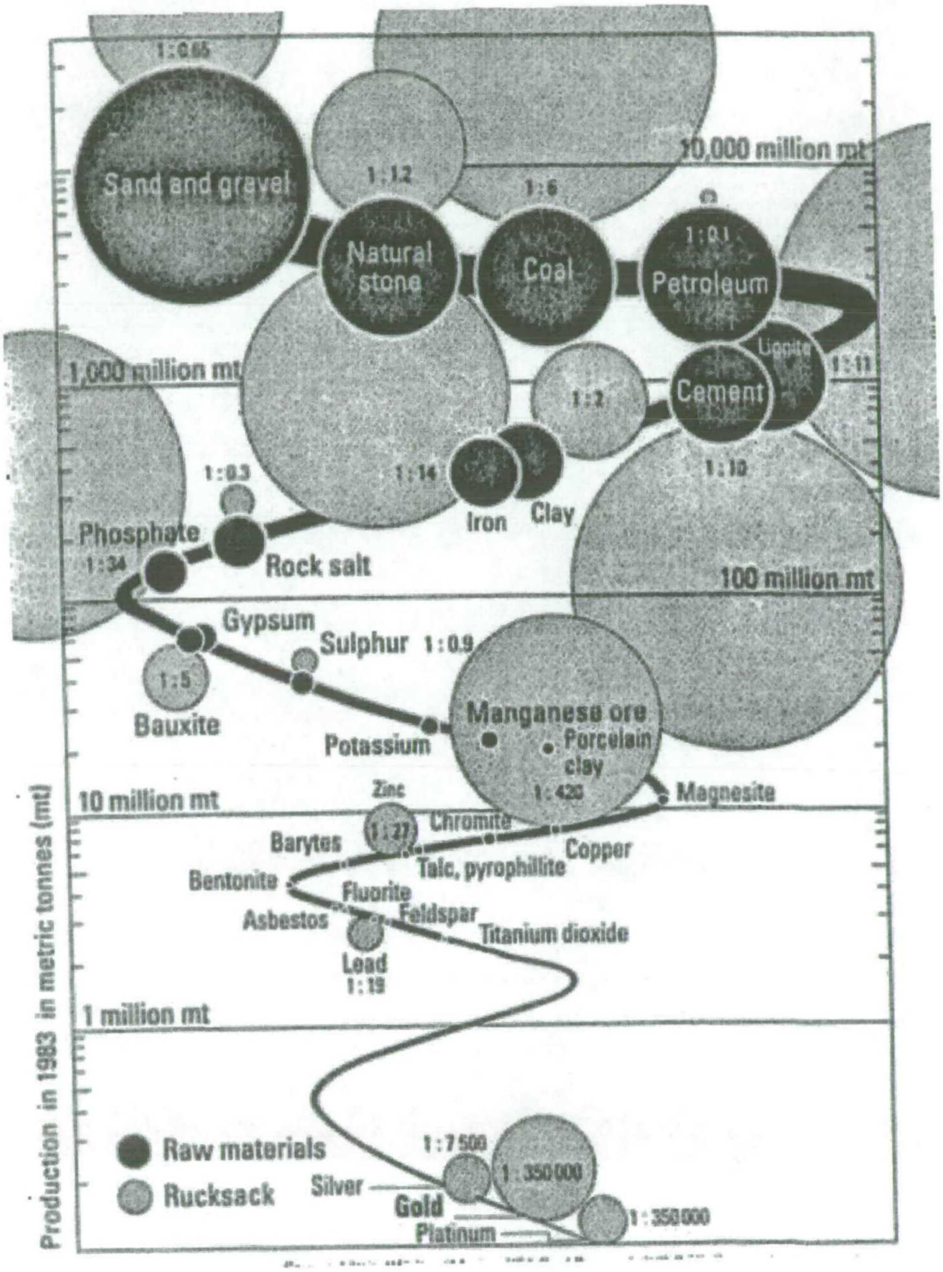

Fig. 1.2 An overview of ecological rucksacks of various materials

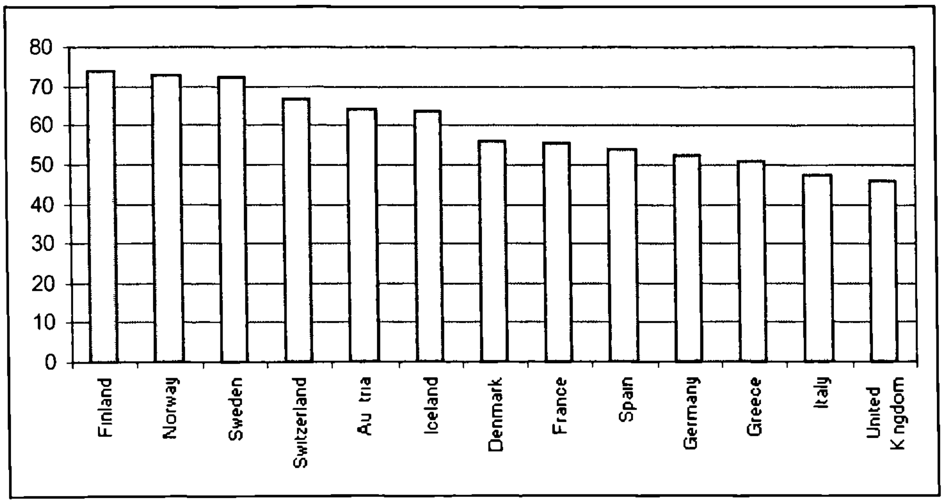

Fig. 1.3 Environmental Sustainabılıty Index – Comparison of European countrıes

Table 1.1 Projections of Future electricity demand by region

Region	1995 (TWh)	1998 (TWh)	2010 (TWh)	2020 (TWh)	Annual growth(%)
OECD-Europe	2678	2875	3836	4492	1.67
OECD-North America	4110	4362	5508	6363	1.54
OECD-Pacific	1190	1236	1613	1865	1.56
Latin America	772	871	1409	2073	2.68
East Asia	608	708	1294	2030	3.33
South Asia	485	568	1070	1657	3.42
China	1036	1234	2497	3857	3.72
Middle East	327	357	513	839	2.57
Former Soviet Union+ Eastern Europe	1631	1777	2491	3298	2.02
Africa	367	408	622	851	2.32
World Total	13204	14396	20852	27326	2.07

Table 1.2 Factors influencing environmental impact associated with buildings

Factor	*Effect on indoor environment*	*Effect on environment*
Design	Yes - Ventilation	Yes - Influencing energy use
Siting Orientation	Yes - Radon exhalation, influence on energy use and indoor temperature	Yes - Effect on landscape
Location and Infrastructure	Yes - Determining quality of incoming air	Yes - Influencing transport to and from building
Building materials	Yes - Exhalation of volatiles	Yes - Life cycle impact with various environmental effects
User behaviour	Yes - Smoking	Yes - Influencing water and energy use
Energy input during use	Yes - Combustion products	Yes - Life cycle impact of energy supply
Water input during use	No	Yes - Life cycle impact of water supply
Demolition/deconstruction	No	Yes - Solid waste

CHAPTER 2: WEATHERING AND ENVIRONMENTAL DEGRADATION

2.1 INTRODUCTION

Weathering is the degradation of a material due to its interaction with the exposed environment. Ollier (1969) defines weathering as:

'the breakdown and alteration of materials near the earth's surface to products that are more in equilibrium with newly imposed physico chemical conditions'.

Every material experiences some sort of degradation during its service life due to its exposure to environmental and surrounding conditions. The environmental factors such as ultra-violet radiation (UV), temperature, humidity, oxygen and pollution can all cause significant detrimental effects on appearance and properties of the material. The natural weathering process results from a complex combination of chemical, mechanical and biological changes, all of which occur simultaneously and affect each other.

Materials are affected by environment in various ways depending upon their nature and sensitivity towards degrading factors. For example, metals get corroded under detrimental conditions but don't experience biological degradation. PVC and timber, on the other hand, undergo biological attacks but not corrosion. Similarly, the severity of UV radiation and temperature is different for metals, PVC or timber. Simpson (1970) speaks on similar lines as, 'All materials deteriorate. Scientific observations show that some deteriorate at a faster rate than others depending on a set of controlling conditions or casual factors'.

Westberg et al (2001) schematically describes the environmental degradation by the following expression.

Agents ⟶ Mechanism ⟶ Effects

An *agent* (e.g. solar UV radiation, heat, moisture, acid, salt, fungi and insects) is a phenomenon in the exposure environment that acts on a construction or a part of it, resulting in a reduction of performance. The *mechanism* governs the process that reduces the performance of an assembly, component or material (e.g. force, breaking of chemical bonds, and corrosion), while an *effect* is the result of the action of agents (e.g. wear, dampness, deformation).

This chapter discusses the composition and characteristics of the three main frame materials investigated in this project, aluminium, PVC and timber (aluminium clad timber is a combination of aluminium and timber, hence, there is no need to describe it separately). The weathering modes of these materials will be described herein as well as the potential protective measures.

2.2 WEATHERING FACTORS

General environmental factors and their weathering impacts can be categorised as follows:

2.2.1 Solar radiation

Solar radiation is composed of 37.8% non-visible light in the wavelength >800 nm, which contributes to heating but does not initiate photochemical reactions in materials; 55.4% of visible radiation between 400-800 nm, which also contributes to heating and is capable of initiating photochemical reactions; and the remaining 6.8% is UV radiation below 400 nm, which has little effect on heating but initiates photochemical reactions that lead to degradation of materials (ISO 4892 as reported by Jakubowicz, 2000). The UV region, as shown in Fig. 2.1, is between the violet end of visible light and the X-ray region, consists of electromagnetic waves, shorter and more energetic than the visible spectrum, having energy enough to initiate some chemical reactions within the material and produce oxidation. UV radiation is considered to be one of the main degradation factors particularly in organic materials; it is responsible for the dehydrochlorinaion in PVC and photo oxidation of timber surfaces (Williams et al, 2000 and Sandberg, 1999).

2.2.2 Temperature

The speed of a chemical reaction increases with the increase in temperature, therefore, higher temperatures increase the deterioration of organic materials, as also described by Jakubowicz et al (1999) and (2000). Warmth stimulates deterioration processes in combination with solar radiation, oxygen and moisture. At low temperatures, materials such as polymers and rubber freeze and become brittle. The cycle of freezing and thawing is a deciding factor for some materials. Wide changes in temperature strain the material, even without frost, and cause it to deteriorate which is also called thermal fatigue.

2.2.3 Wind and rainfall

Wind and rainfall are most damaging to materials when they occur simultaneously. When it occurs, moisture can force its way into the material and start off the deterioration process. Strong winds cause pressure in material which may even lead to fracture or collapse. Combined with sand, wind can have a devastating effect on certain materials. The weight of snow can also break down structures (Berge, 2001). Figures 2.2 (a) & 2.2 (b), provided by Environmental Engineering (EE, 2000), show interesting examples of damage caused by rain and wind onto aircraft. Again, Figs 2.3 (a) & 2.3 (b) specifically describes the impacts of rain and wind on a timber window.

2.2.4 Relative Humidity

Change of relative humidity affects deterioration by causing changes in volume and stress within the material. Increased humidity increases the rate of deterioration.

2.2.5 Chemicals

In coastal regions, the salt content of the air can deteriorate materials. In industrial and those areas where traffic is significant, aggressive gases such as sulphur dioxide can break down a variety of different materials. Figure 2.4 shows an excellent example of deterioration of a statue due to chemicals and humidity (geooeko web reference).

2.2.6 Changeability of climate

Changeability or variability of climate conditions can also be significant towards the weathering of materials, as indicated by Ollier (1969). An occasional longer period of excessive drought, high temperatures or excessively low temperatures may achieve a great deal of weathering than is achieved under steady conditions.

2.3 ALUMINIUM

Aluminium is one of the most abundant elements in nature, Haupin (1987) reports that aluminium makes up more than 8% of the earth's crust. Aluminium is not found free in nature but in combination with silicon and oxygen and frequently iron in rock or clay, named bauxite. Pure aluminium is a silvery-white, soft, ductile and corrosion-resistant metal. By alloying with other metals a range of materials is produced which, by retaining the common characteristics of lightness and durability, give considerable increase in tensile strength and hardness. The strength of aluminium can be varied by alloying and by cold working or heat treatment. There are however a number of properties which are more or less constant for pure aluminium and its alloys. Aluminium alloys are normally classified into following eight series.

1XXX; Aluminium based
2XXX; Aluminium copper alloy - principal alloying element is copper
3XXX; Aluminium manganese alloy - principal alloying element is manganese
4XXX; Aluminium silicon - principal alloying element is silicon
5XXX; Aluminium magnesium alloy - principal alloying element is magnesium
6XXX; Aluminium magnesium-silicon alloy - principal alloying element are magnesium and silicon
7XXX; Aluminium zinc-magnesium alloy - principal alloying element are zinc and magnesium

8XXX; miscellaneous alloys, e.g. aluminium lithium alloys

Amongst the most striking characteristics of aluminium is its versatility. The range of physical and mechanical properties that can be developed from refined high purity aluminium to the most complex alloys is remarkable. Rooy (1990) states that more than three hundred alloy compositions of aluminium are commonly recognised. Amongst leading characteristics of aluminium include its high strength to weight ratio, excellent physical and mechanical properties and corrosion resistance. Aluminium is non toxic and has excellent electrical and thermal conductivity. In less than 100 years, aluminium has become one of the most widely used materials in the building and construction sector. Aluminium products are valued in the construction sector because of following characteristics;

- Their versatility and ability to be formed into different shapes
- Their lightness that results in lower load bearing on structures
- Their ease of processing
- Their good mechanical strength
- Their high corrosion resistance
- Their long life expectancy
- Their excellent recycling properties
- Their lack of pollution in case of fire damage
- Their ability to be anodised in a wide range of colours

2.3.1 Weathering of aluminium

Although aluminium is a very reactive metal with a high affinity for oxygen, the metal is highly resistant to most environments and to a great variety of chemical agents. This resistance is due to the inert and protective character of the aluminium oxide film which forms on the metal surface. The metal's natural coating of aluminium oxide provides a highly effective barrier to the degrading attacks of air, temperature, moisture and chemicals. This oxide film normally gets dissolved in strong acids or alkalis, however is quite stable in a pH range of 4 to 9 according to Lifka (1995), while the Aluminium Federation (1999) reports this stable pH range between 4 and 8. For aluminium, passivity is found in near neutral solutions, but in solutions with low and high pH values the oxide will dissolve, thus leading to corrosion. In solutions containing chloride ions, aluminium will be attacked in the form of localised corrosion, i.e. pitting corrosion. This is the most commonly encountered form of aluminium corrosion.

2.3.2 Corrosion

Corrosion is the destruction or deterioration of a material (normally metallic) because of its reaction with its environment. Corrosion is defined in the Encyclopaedia of Physical Science and Technology as:

'the damage of a metal by chemical reaction with its environment' (Bradford, 1987).

Corrosion is a natural process and is a result of the inherent tendency of metals to revert to their more stable compounds, usually oxides.

2.3.2.1 Different forms of corrosion

Fontana (1988) categorises corrosion into following main types;

1. Uniform or general attack
2. Pitting
3. Crevices
4. Galvanic or, two or more metal alloy
5. Intergranular
6. Erosion
7. Stress
8. Selective leaching or parting

2.3.2.2 Electrochemistry of corrosion

Since corrosion is basically an electrochemical process, it requires the existence of four conditions to proceed.

- A positive or anodic area, normally a metal, referred to as the "anode."
- A negative or cathodic area (e.g. metal or graphite electronic conductor) referred to as the "cathode."
- A path for ionic current flow, or "electrolyte."
- A path for electronic current flow, which is normally a "metallic path."

The electrical potential between the anode and cathode causes the corrosion current to flow. The anode is the area that suffers metal loss and corrosion. The amount of metal that will be removed is directly proportional to the amount of current flow. This rate varies from metal to metal, and the corrosion current normally encountered is of the order of milliamperes.

2.3.2.3 Chemical reaction at the corrosion cell

A metal surface exposed to a conducting electrolyte of the sort provided by rain water containing salts becomes the site for two chemical reactions. There is an oxidation or anodic reaction that produces electrons as, for example;

$Fe \quad Fe^{++} + 2e^-$ (3.1)

There is also a reduction or cathodic reaction that consumes the electron produced by the anodic reaction, for example;

$O_2 + 2H_2O + 4e \quad 4OH$ (3.2)
$O_2 + 4H^+ + 4e \quad 2H_2O$ (3.3)
$2H^+ + 2e \quad H_2$ (3.4)
$Fe^{++} + 2H_2O \quad Fe(OH)_2 + 2H^+$ (3.5)

Because these anodic and cathodic reactions are occurring simultaneously on a metal surface, they create an electrochemical cell. The sites of the anodes and cathodes of the corrosion cell are determined by many factors and can be adjacent or widely separated. For example if two metals are in contact, one metal can be the anode and the other the cathode, leading to the galvanic corrosion of the anodic metal.

At the anodic sites dissolution of the metal as metallic ions in the electrolyte occurs. This destructive process is called corrosion The flow of electrons between the corroding anode and non-corroding cathode is called corrosion current. Its value is determined by the rate of production of electrons by the anodic reaction and their consumption by the cathodic reaction (Kruger, 1991).

2.3.3 Protection of aluminium

There are a number of surface treatments available to further protect aluminium against weathering conditions. Alves (2001) has reported different surface treatments for aluminium such as;

- Powder coating
- Anodising
- PVF_2, Plastisol
- Enamelling
- Passivation

Powder coating and anodising, being the common techniques applied on windows, are discussed in the following sections.

2.3.3.1 Powder coating

Powder coating is a relatively new metal coating technique and was first introduced in the early 1970's. Adams (1998) classifies powder coatings into two basic types; thermoplastic and thermosetting, the latter being the preferred choice of the construction sector. Thermosetting powders are further classified into four types; epoxies, polyesters, polyurethanes and acrylics. Polyester thermosetting powder however, is the most commonly specified product because of its good resistance to natural weathering, a high degree of colour fastness, adequate mechanical properties and good chemical and corrosion resistance.

In this process, powdered resins along with coloured pigments are applied to metal products using an electro-static charge. The product is then baked in a high temperature oven causing the powder to melt, flow, and then cure, forming a molecular fusion bond that is the strong surface-to-coating bonding.

2.3.3.2 Anodising

Anodising is an electro-chemical process in which the natural oxide film on aluminium is thickened by passing an electric current through an acid electrolyte, e g., sulphuric acid, with the aluminium part as the anode. The anodised surface is a protective inert film of aluminium oxide and is 'self healing', making it more tolerant to minor scratches and abrasion.

The basic anodising process consists of a chemical pre-cleaning dip, followed by etching in a caustic soda base solution, anodising electrolytically in a sulphuric acid or other solution, and finally sealing to reduce porosity. Varying the electrolyte composition and modulating the process parameters allows the production of coatings bearing specific properties. The thickness of the film and the degree of sealing after anodising or drying are the most important factors determining the durability of the finish. Figure 2.5 shows the main process steps in an anodising line and solution compositions.

2.4 TIMBER

Timber is a biological material that is widely used in construction. Blodgett (1990) reports that there are more than 30,000 species of timber in the world and BRE (1999) outlined specifications of more than a hundred types of timber. Timber can be broadly divided into two types; hardwood and softwood. The terms have no reference to actual softness or hardness of the timber, as also described by Miller (1999), Levin (1971) and ASTM Standards (D9-87), since some softwoods are actually harder than some hardwoods and conversely some hardwoods are softer than some softwoods. For example, softwoods such as longleaf pine and Douglas fir are typically harder than hardwoods basswood and aspen.

2 4.1 Hardwood

Hardwood timber has its source in broad-leave trees. They are generally hard, tough and dark-coloured with an acrid, aromatic or even poisonous secretion, although not all hardwoods are hard. Botanically, hardwoods are Angiosperms with the seeds enclosed in the ovary of the flower. Anatomically, hardwoods are porous and contain vessels like elements. Typical examples of hardwood are; oak, teak, walnut, mahogany, and elm.

2.4.2 Softwood

Softwoods are normally cone-bearing trees having needle or scale-like evergreen leaves. They are usually elastic and easily worked, with resinous or sweet secretions. Some softwoods like pitch pine are quite hard. Botanically softwoods are Gymnosperms; the seeds are naked (not enclosed in the ovary of the flower). Anatomically softwoods are non-porous and do not contain vessels. Typical examples of softwood are; European redwood, yellow pine, Douglas-fir, Whitewood, and Canadian spruce.

2 4.3 Physical and chemical composition of timber

Two of the most important physical properties of timber are its moisture content and density. These are important since they influence many other physical and mechanical properties. For example, the relative amount of water in timber affects the mass, decay susceptibility, permeability, strength, heat transfer properties, adhesion and dimensional stability. In general, the properties of timber depend on a variety of factors such as species, geographic area where the tree grew, the growth conditions and the size of the tree at harvest; other factors such as drying and manufacturing processes are also vital in case of assessing timber products.

Chemically, timber mainly consists of cellulose, lignin and hemi-cellulose with minor amounts (5%-10%) of extraneous materials. Cellulose constitutes 50% of the timber substance by weight. Lignin constitutes 23%-33% of the timber substance in softwood and 16%-25% in hardwood. The hemicellulose are associated with cellulose and are composed of several kinds of pentose and hexose sugar monomers.

The structure of timber is one of an orderly arrangement of cells made of the elements mentioned below. Variation in the characteristics and volume of these substrates and differences in cellular structure make timber light or heavy, stiff or flexible and hardwood or softwood. Figure 2.6, by Levin (1971) shows the typical texture of timber consisting of following main elements;

2.4 3 1 Timber cells

Timber cells are the basic structural units and these can be of various sizes and shapes, firmly attached together. Cells are classified into different types such as fibres, vessels or pores, and longitudinal or axial parenchyma cells having particular cavities and cell walls.

2 4 3.2 Pith

This is the small, soft tissue occurrmg in the structural centre of a tree trunk, branch, or log.

2.4.3.3 Heartwood

This is the inner layer of a timber stem wholly composed of non-living cells and usually dıfferentiated from the outer envelopıng (sapwood) by its darker colour.

2.4.3 4 Sapwood

Thıs contains both livıng and dead tissues, formıng the ınitial layer of timber beneath the bark of the log. It functions normally ın the storage of food and carries sap from the roots to the leaves.

2.4.3.5 Bark

This is the layer of a tree outside the cambium and is made up of the inner bark and outer bark. Inner bark, in the living trees, is generally moist and soft. Outer bark also called dead bark is on the outside and frequently is corky and dry.

2.4.3.6 Cambium

This is the layer of cells that lies between the inner bark and the timber of a tree, that repeatedly subdivides to form new wood and bark cells.

2.4.3.7 Annual ring

This is the growth layer produced by the tree ın a single growth year.

2.4.3.8 Early wood

Early wood or spring wood is the less dense, large-celled part of the growth layer formed first during the annual growth cycle.

2.4 3 9 Late wood

Late wood or summer wood is the denser, smaller celled, later-formed part of a growth layer

2.4.4 Weathering of timber

Naturally, timber is a quite durable material that can last even for centuries as reported by Berge (2001) in Table 1. The long-term performance of timber is, however, influenced by both biological and non-biological factors. Biologically timber is affected by fungi (wet and dry rot type) and insects such as termites, beetles and marine borers. Non biological degradation of timber is generally classified as weathering. Weathering in timber is the degradation phenomenon that occurs through photo-oxidation of the surface catalysed by the ultra-violet (UV) radiation in sunlight, and it is supported by other processes such as washing by rain, changes in temperature, abrasion by windblown particles and changes in moisture content. Since all these factors do not normally coincide, weathering is a cyclic process. In Fig. 2.7, Feist (1991), shows in detail the weathering factors and their impacts on the timber.

2.4 4.1 Steps in weathering of timber

Feist (1991) states that the first step in weathering process is the change of colour, to a yellow or brown colour. This colour change begins in the surface as soon as the timber is exposed to sunlight. The change occurs because the sunlight especially ultra-violet light decomposes the lignin, which as discussed previously, constitutes from 16% to 33% of the timber and is the chemical structure that holds the individual cells together.

As weathering continues a grey layer develops (Fig 2.8). This layer is composed of loosely matted fibres of nearly pure cellulose because rain or moisture leaches out the decomposed brown-coloured lignin. The grey colour of the surface layer of weathered timber usually results from the growth of staining micro-organisms called fungi and commonly called mould or mildew. Certain species of these organisms grow wherever a sporadic supply of moisture is available, and can produce a uniformly weathered and grey appearance on the timber surface within a year. Micro-organisms may also produce dark coloured spores and mycelia, which can produce the dark grey, blotchy and unsightly appearance of some weathered timber. All wood surfaces eventually turn grey upon exposure to sun and rain.

2.4.4 2 Rate of weathering

Once the weathered grey colour is produced, additional changes in the appearance of the timber occur very slowly because the process affects only the surface of the timber. The rate of weathering is affected by climatic conditions, the severity of exposure, timber density, the amount of earlywood and latewood and ring orientation, as well as the rate of growth and probably lignin and extractive content. In general, the less dense the material and more severe the exposure, the faster the weathering and erosion rate. Weathering of timber is typically faster at the beginning how ever this process is so slow that the research indicates, as described by Wypych (1995), Feist (1991) and Williams (2000), that weathering related erosion of exposed wood occur at an approximate rate of 6mm/century. Figure 2.9, as provided by Feist (1991), shows the gradual weathering of timber over 100 years.

2.4.4 3 Surface deterioration

In addition to chemical and colour changes, mechanical damage occurs on the exposed timber surface, mostly as a result of moisture. Water vapour is absorbed or dispersed with changes in relative humidity. Rain or dew in contact with the unprotected timber is quickly absorbed by the timber surface. As the moisture content of timber changes, swelling and shrinking take place and stresses in the surface of the wood result.

The moisture, in combination with the sunlight, causes microscopic and then macroscopic intercellular and intracellular cracks and checks. Face-checking, warping, and cupping can occur with subsequent nail loosening. Grain raising due to differential swelling and shrinking of early wood and latewood can also result. There is a loss of strength in the cell wall bonds near the timber surface, and as rainwater continues to wash the softened surface, the surface becomes increasingly uneven and slowly erodes.

2.4.5 Weathering protection of timber

Surface finishes or coatings can protect timber underneath from ultraviolet radiation and reduce erosion by other weathering factors. It can also result in an extended service life by improving the dimensional stability of timber products in service by minimising the response of timber to changes in humidity and the uptake of liquid water. Different finishes and treatments provide various degrees of protection. The performance of a surface finish depends upon a number of factors such as the characteristics of the finishing material, details of application, properties of the timber substrate and severity of exposure.

Timber can be protected from erosion effects of weathering through use of finishes either a pigmented film forming finish, or a penetrating stain containing ultraviolet inhibitors or blocks. In either of these cases, regular maintenance is important to maintain adequate resistance to weathering.

Applying finishes, which include film forming coatings such as paint, and non-film forming coatings such as transparent and semi-transparent stains, have traditionally been used to protect timber and timber products. In film forming paints, timber-protection is achieved by the action of the film in absorbing the high-energy UV wavelengths. In semi-transparent and transparent stains, this is accompanied through the addition of pigments, with more pigments providing more protection, or other UV blockers or absorbers. Some finishes contain biocide, which can reduce or minimise the growth of mould fungi in damp climates. In order for a finish to be most effective, it is to be maintained on a periodic basis.

Vacuum impregnation of timber parts before painting is a famous preservation technique that protects timber against decay and dry rot. Timber is placed into a vacuum chamber where it is worked with a rot-preventive substance This penetrates to the surface of timber, and up to 5 mm inside it, along the grain up to 50 mm.

2.5 PVC

Polyvinyl chloride is one of the most common synthetic materials, commonly known as 'PVC'. It is comprised of chlorine, carbon, and hydrogen. PVC resin has almost 51-57% chlorine as reported by Green Paper (2000) and Berge (2001). The rest is hydrogen and carbon, both of which are derived from fossil fuels - primarily natural gas and petroleum.

PVC is a versatile resin, appearing in a wide range of different formulations and configurations, and is by far the most common polymer material used in construction. Various studies, for example, Green Paper by the Commission of the European Communities (2000), have reported that the major use (amounting to 57 %) of PVC is in the construction sector not only in the UK but also in Europe as a whole (Fig. 2.10). PVC is a thermoplastic material i.e. it can be melted by heating and transformed into shapes required through various process. The material regains its original properties after it is cooled. The main methods used in PVC fabrication are injection moulding, blow moulding, extrusion compression moulding, rotation moulding, calendering and thermoforming.

Pure PVC is a rigid material, mechanically tough and relatively unstable to heat and light. A number of additives or modifiers are added to PVC to enhance its base characteristics - stabilisers and plasticisers being the most important additives. Stabilisers help in maintaining the physical and chemical properties of PVC. Plasticisers, normally non-volatile organic liquids or low-melting point solids, function by reducing the intermolecular forces in a resin thus permitting the macromolecules to slide over one another more freely. As a result, the brittleness of PVC is reduced and there is an increased ease of processing. A typical polymer compound may contain the following ingredients in various proportions.

- Polymer
- Stabilisers
- Plasticisers
- Extenders
- Lubricants
- Fillers
- Pigments
- Polymer processing acids
- Impact modifiers

Other miscellaneous materials are also used occasionally such as, fire retardants, opti al bleaches and blowing a ents.

Crawford (1999) categorises PVC into two main types, plasticides and unplasticides. Plasticides PVC is flexible and finds applications in wire covering, floor tiles, toy balls, gloves and rainwear. Unplasticides PVC (uPVC) is a hard , tough and strong material which is widely used in construction industry. For example pipes, gutters, window frames and wall claddings are all made in this material.

2. 5.1 Weathering of PVC

PVC is a heat sensitive material which deteriorates under UV exposure and other environmental factors Weathering properties of PVC depend on its formulation and manufacture (suspension polymerisation or emulsion polymerisation), as highlighted by Davis et al (1983) and Simpson (1970). Since PVC is produced in a wide range of formulations, weathering characteristics of any particular PVC product can not be defined clearly unless its composition and processing mode is known.

Degradation of PVC due to weathering is a free-radical mechanism started by the absorption of sufficient energy to break chemical bonds. Degradation causes changes in its chemical structure and physical properties leading to materials with characteristics different from those of the starting material. PVC undergoes a dyhydrochlorination process which is characterised by the formation of Polyene sequence resulting into discoloration. It is also reported by El Raghi (2000), that in the presence of oxygen and moisture the dyhydrochlorination results into formation of 'water washable' products as well as cross linking, besides Poylene formation and subsequent scission of chains. Alger (1990) describes dehydrochlorination as a sequential reaction by unzipping loss of hydrogen chloride, resulting in the formation of conjugated double bond sequences (polyenes) which absorb visible light and the degraded polymer is discoloured. The following equation describes the dehydrochlorination process; formation of polyene and resulting HCl.

$$-CH_2-CHCl-\rightarrow \quad CH-CH-+HCl \tag{3.6}$$

HCl evolved during the degradation of PVC can remain in the degraded polymer which catalyses further degradation. The presence of oxygen also accelerates the thermal dehydrochlorination of the material as referred by a number of researchers, amongst them Jellinek (1983) and Mark et al (1982).

2.5.2 Weathering protection of PVC

The basic PVC resin alone is not stable enough to be used, so it is always mixed with additives to improve its characteristics as well as to stabilise it against weathering impacts. Additives used to improve weathering resistance properties of PVC are referred as stabilisers - defined as an agent used in compounding polymers to assist in maintaining the physical and chemical properties of the compounded materials at suitable values throughout the processing and service life of the material. Primarily stabilisers are added to PVC to make it stable against heat and light.

Traditionally, heavy metals such as lead and cadmium are used as stabilisers (Green paper, 2000). However, due to increased concerns of toxicity resulting from these elements, the PVC industry is switching towards other materials; mixed metals such as calcium-zinc and barium-zinc, and liquid formulations are more common now, as discussed by Jakubowicz (2000) and EBN (1994). Stabilisers are also classified according to their functions such as UV stabilisers, light stabilisers and antioxidants, which further can be branched into many types.

2.6 DURABILITY OF COATINGS/FINISHES

Coatings have two primary functions – surface protection and decoration. There are a few considerations regarding the performance of coatings, as given below;

Like coated products, coatings themselves receive weathering impacts during their exposure. Factors, influencing the coating durability and the sequential process of coating's degradation are shown by Wypych (1995) in Fig 2.11.

It is important to choose the right coating for the right surface. Timber, for example, is an organic material which swells in damp conditions and shrinks in dry weather depending upon its moisture content. These conditions should therefore be considered when choosing the surface finish.

Proper pre-treatment of any surface, including timber and aluminium, is essential to achieve desired levels of durability of the surface finishes. In Figs 2.12 (a) & 2.12 (b), Feist (1991) indicates the difference made by the proper treatment on the performance of coatings. Similarly, Alves (2001) states that any variations from an established procedure of anodising can produce defective coatings, resulting in reduced life span of coating.

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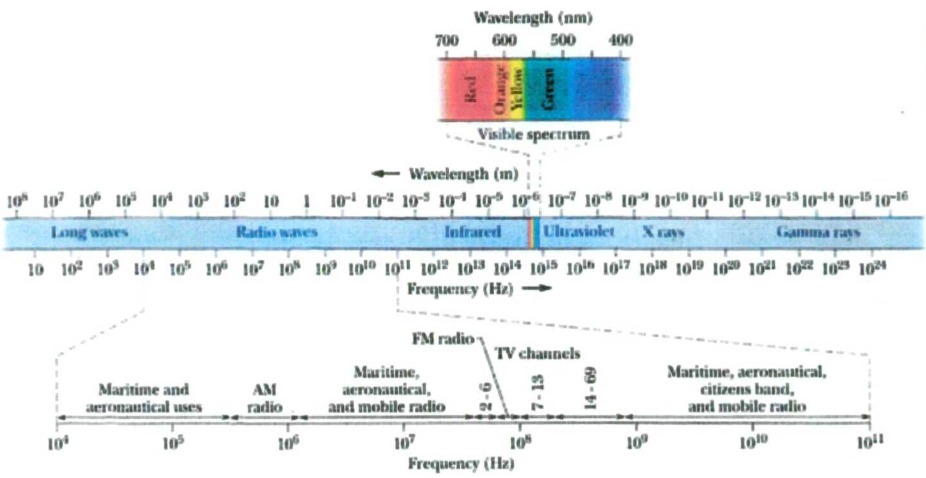


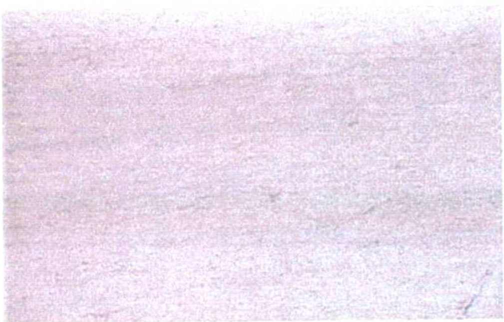
Fig. 2.1 Solar spectrum, showing the radiation details

Fig. 2.2 (a) Erosion of Air craft surface due to rain and wind

Fig. 2.2 (b) Damage caused by heavy hail to an American Harrier

Fig. 2.3 (a) Fixed (top) end of window is less deteriorated as compared to open (bottom) end that is more exposed to flux of wind and moisture

bottom



top

Fig. 2.3 (b) Microscopic image showing difference of the more exposed (left) and lesser exposed surface (right)

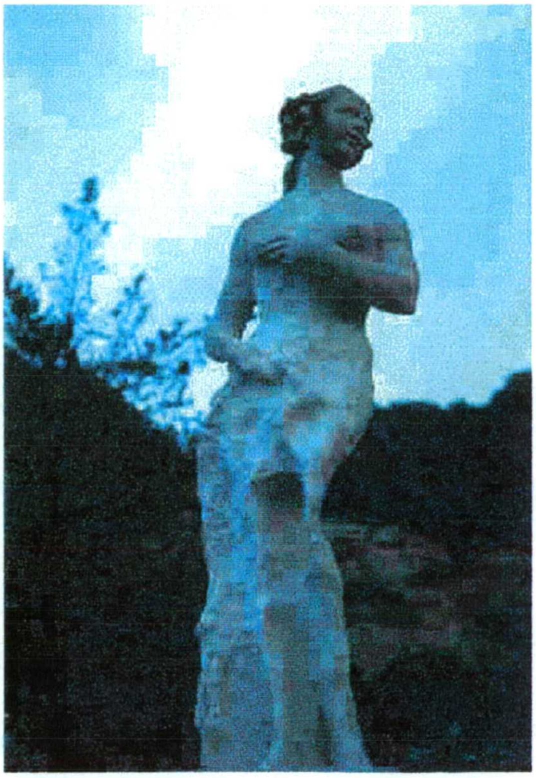


Fig. 2.4 Weathering - bottom of the statue at a thermal bath at Ischia, Italy, has been attacked by salty vapours

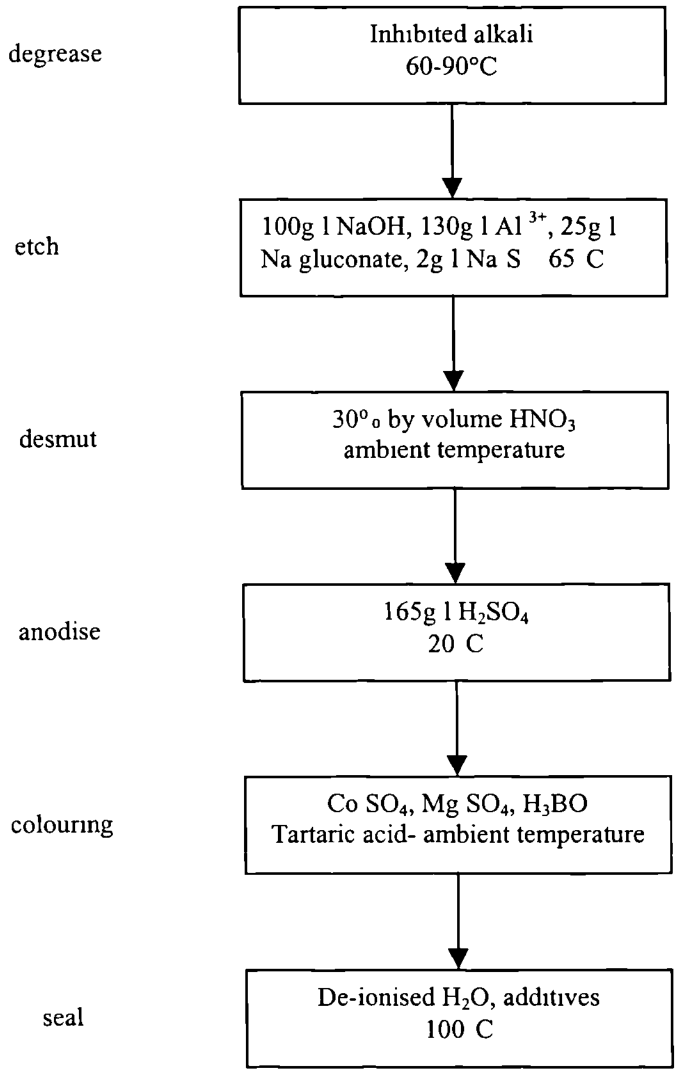


Fig. 2.5 Schematic diagram showing the main process steps in an anodising line and solution compositions

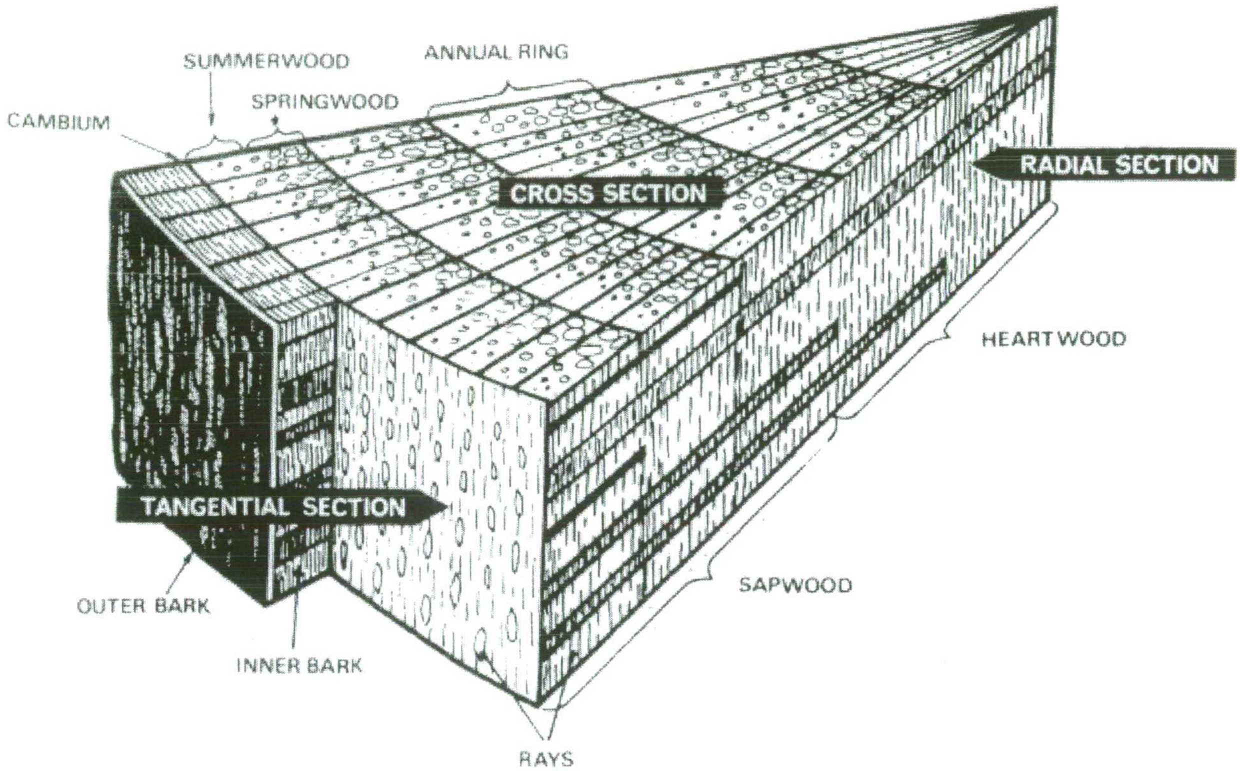


Fig. 2.6 Cross section of wood

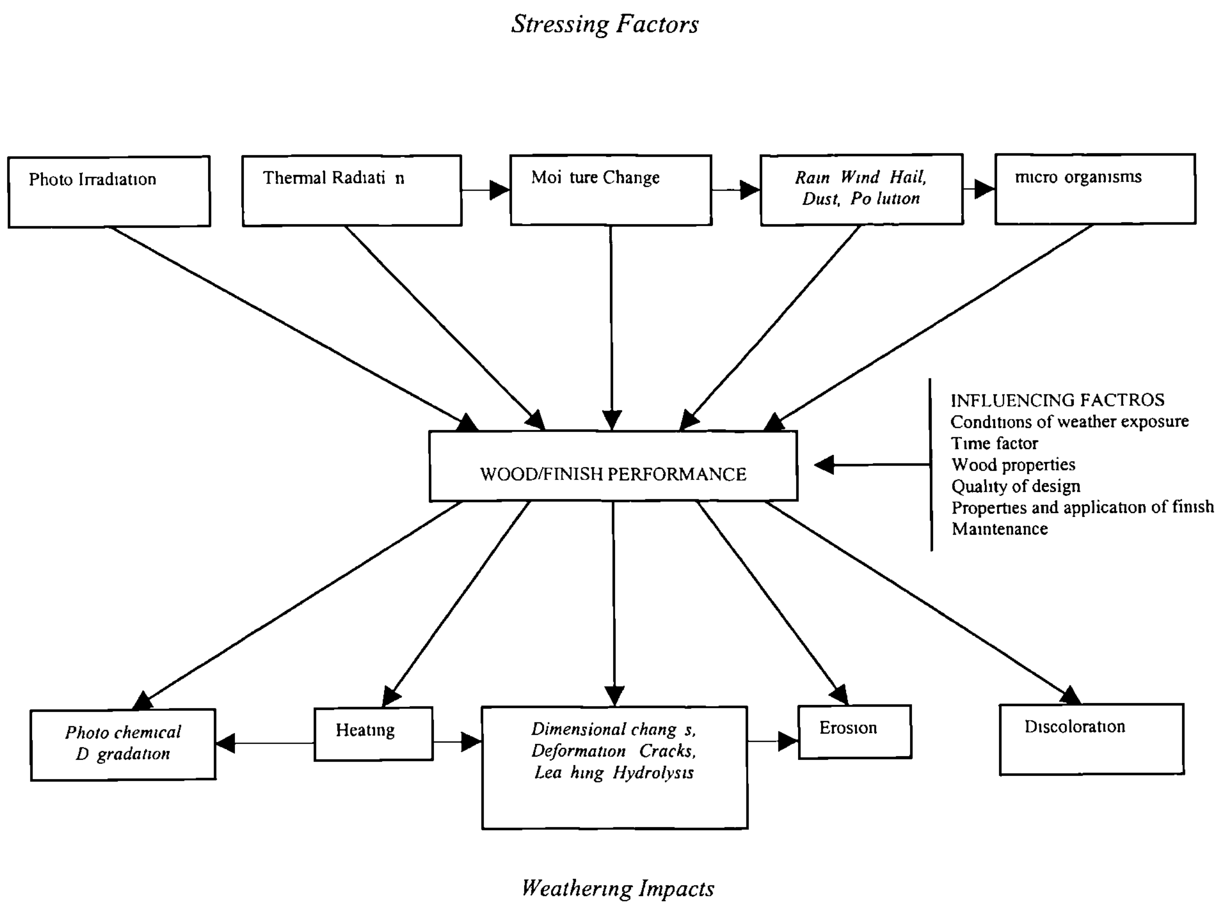


Fig. 2.7 Weathering factors and their impacts on timber

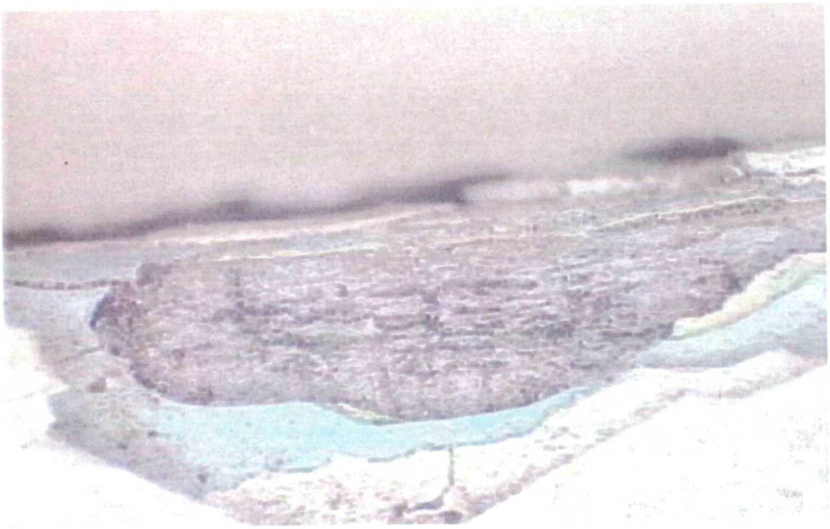


Fig. 2.8 The microscopic view of the weathering of a timber window –weathered grey timber is visible

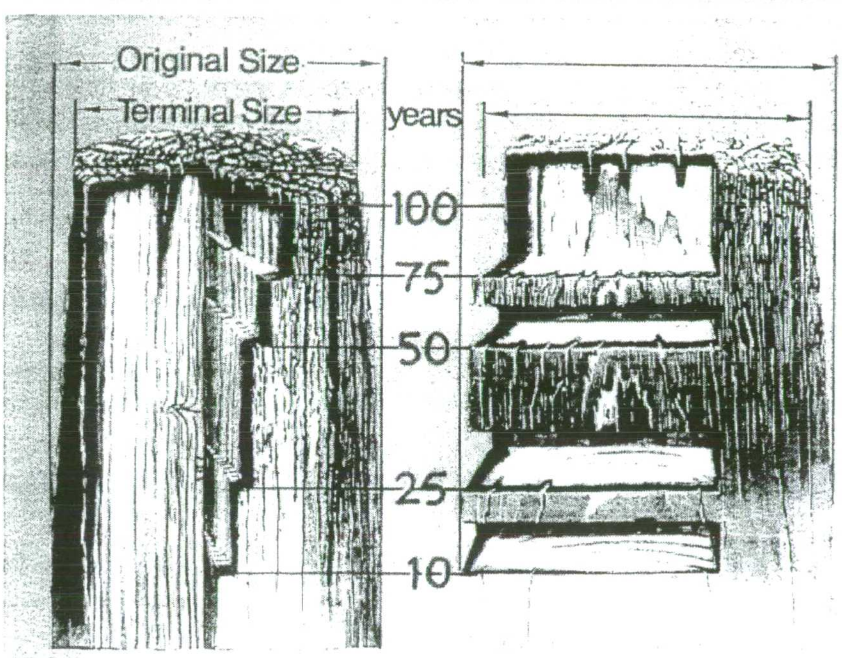


Fig. 2.9 The weathering process of round and square timbers; cutaway shows that interior wood below the surface is relatively unchanged

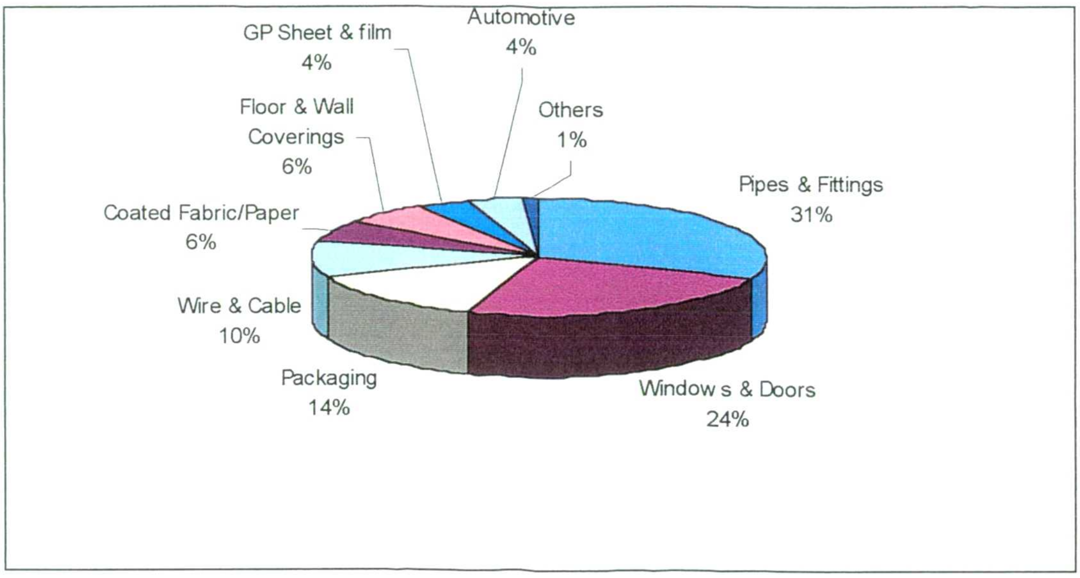


Fig. 2.10 Estimated UK end-uses of PVC

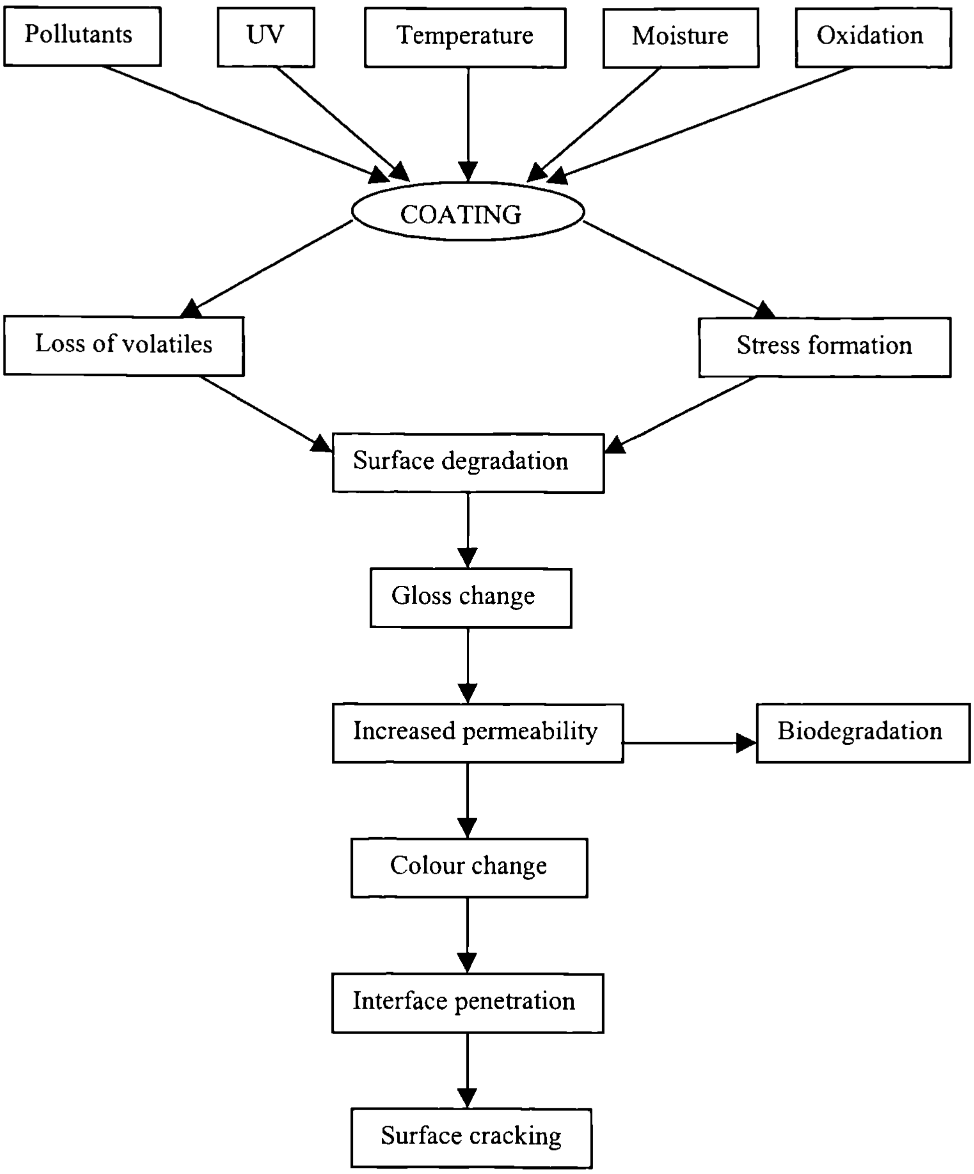


Fig. 2.11 Sequence of events durıng coating degradation

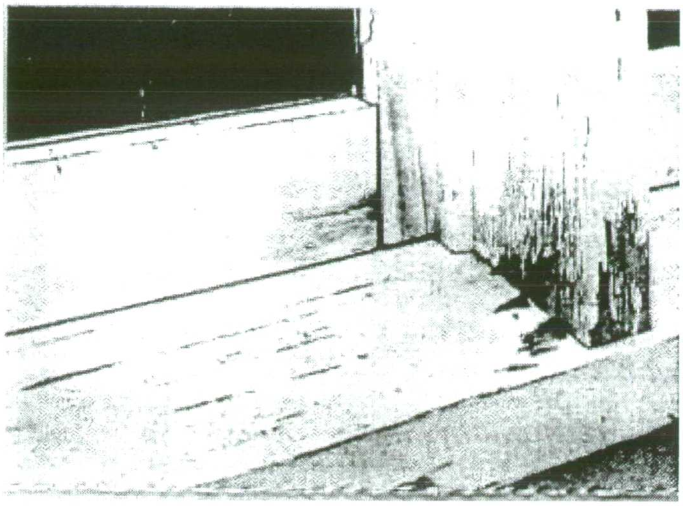


Fig. 2.12 (a) Timber window having not treated before painting, resulted into severe weathering upon 5-year exposure

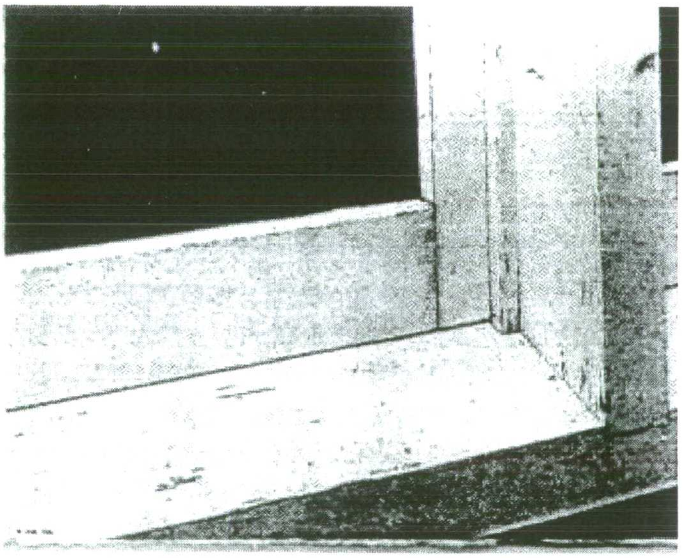


Fig. 2.12 (b) Timber window having been treated with water repellent preservative before painting, shows good condition after 5-year exposure

Table 2.1 Durability of timber in years in different situations

Timber	*Always dry*	*Sheltered outside*	*Unsheltered outside*	*In contact with earth*	*Underwater*
Pine	120–1000	90–120	40–85	7–8	500
Spruce	120–900	50–75	40–70	3–4	50–100
Larch	1800	90–150	40–90	9–10	More than 1500
Juniper	–	More than 100	100	–	–
Oak	300–800	100–200	50–120	15–20	More than 500
Aspen	–	Low	–	Low	High
Birch	500	3–40	3–40	Less than 5	20
Maple	–	–	–	Less than 5	Less than 20
Ash	300–800	30–100	15–60	Less than 5	Less than 20
Beech	300–800	5–100	10–60	5	More than 300
Elm	1500	80–180	6–100	5–10	More than 500
Silver fir	900	50	50	–	–
Willow	600	5–40	5–30	–	–
Poplar	500	3–40	3–40	Less than 5	–

CHAPTER 3: WEATHERING PERFORMANCE EVALUATION THROUGH ACCELERATED TESTS

3.1 INTRODUCTION

The performance and durability of materials and products are related to their resistance against detrimental environmental conditions. Accelerated testing is a useful evaluation technique to assess the weathering performance of materials. Its widespread use has been highlighted in numerous studies, for example, Spence (1995) describes the prime significance of accelerated tests to examine the performance of materials, evaluate alternate materials, develop strategies for protection of materials, and obtain corrosivity information on specific environments.

In their service life, windows experience environmental conditions that cause gradual degradation affecting their appearance as well as durability. In present work accelerated testing has been adopted as the weathering performance assessment tool for the window frames. This chapter provides a brief introduction of accelerated testing in terms of basic characteristics, scope and limitations. The tests carried out and their results have also been described in detail.

3.2 INTRODUCTION TO ACCELERATED TESTING

Weathering or corrosion tests can be broadly classified into two main types; laboratory tests and service tests. In service tests, materials experience real life conditions to assess their performance. Difficulties associated with long-term testing, including the need for rapid assessment of materials has led, over the years, to the introduction of various forms of accelerated testing which has become an important practice now in the development of materials.

Accelerated testing has been used since the early 1900s as a means of evaluating the performance of materials. In accelerated tests, one or more environmental factors is intensified so that the degradation process takes place more rapidly. The results are obtained after a time, much shorter than in real life, which according to Wranglen (1985) may be counted in weeks, days, hours or even in minutes.

Accelerated tests can be conducted in closed cabinets or chambers (as shown in Fig. 3.1) where the conditions of exposure can be controlled. The objective is to intensify corrosion process in a controlled manner without changing the mechanism of corrosion. The theme of the accelerated testing is to maximise the time when corrosive conditions exist and to accelerate degradation of the material . This eliminates the long periods of time which can occur during normal exposure when there is little or no corrosion. There are hundreds of established accelerated test methods, as documented in the literature, used for testing different materials and under different intended environments. Table 3.1 shows some of the tests methods relevant to this work.

3.2.1 Simulation of atmospheric conditions in test chamber

A fundamental principle in the choice of accelerated tests is that the testing environment in terms of its qualitative chemical composition, should essentially be the same as in the corresponding practical case. In accelerated testing, an attempt is made to produce a certain acceleration of the degradation process by a change in degree; that is, by intensifying some dominating environmental factors such as UV, moisture, temperature, or the concentration of a certain corrosive agent. A few accelerated testing techniques, to simulate actual environmental conditions are given below.

- Salt spray can be used if the purpose is to simulate coastal atmospheric conditions.
- Sulphur dioxide is used if the purpose is to intensify the corrosion in industrial atmospheres.
- Ammoniacal atmosphere may be imitated by using ammonia solution.
- UV fluorescent lamps can be used to produce the effects of the solar UV radiation.
- Oven can be used to simulate severity of temperature.
- Moisture spray can be used to simulate humidity, rain or dew.

3.2.2 Evaluation of results

The evaluation of results is often dictated by the purpose of the test. In the case of quality control, comparison with a reference or base line material may be appropriate. The key is to ensure that the evaluation criteria are relevant to the intended purpose of the material being tested.

3.3 SCOPE AND LIMITATIONS OF ACCELERATED TESTING

Accelerated tests have been widely used in industries to provide a useful means of comparing different materials with an acceptable standard. These tests have become very vital in the development of new materials and products in a wide range of sectors such as aerospace, automotive, construction, chemical, electronics, and coating industries. The pace of materials development is often dictated by the availability of accelerated tests since one can not wait for degradation to occur under natural conditions. It is obvious that in the development of new materials and coatings and other methods for surface protection, it is not possible to resort immediately to long-term model or plant tests and still less so to field tests. In the beginning, it is necessary, to use accelerated tests. These should be used and applied in such a way, however, that the results have the highest possible relevance for the practical application.

The natural environment consists of a system of constantly changing humidity, temperature, wind speed and direction, light intensity, particulate content, chemical composition , precipitation, and other factors. Under such a variety of existing conditions, the state of an exposed surface in a natural environment is not predictable at any moment in time. One of the basic features of accelerated tests is their predetermined testing environment which may be composed of a single condition or a combination of conditions acting collectively or in cyclic order. It is therefore, difficult for accelerated tests to correctly replicate the natural exposure.

Accelerated testing is predominantly a means for assessing the durability of materials under particular conditions. It however, does not provide any information about the service life of the materials since no exact correlation can be obtained between the accelerated test results and natural environmental exposure - it provides no such information that so many hours of accelerated exposure resembles with this much duration in natural atmosphere. This particular characteristic of accelerated tests has been highlighted by a number of authors such as Gardette (1993), Shreir (1979), Wranglen (1985) and Appleman (1990). Alblas (2000) speaks on similar line stating that all durability tests, including outdoor exposures, are relative tests. They do no give absolute prediction of how many years a material will last in actual service. Jakubowicz et al (1999) reports a correlation between accelerated ageing and real life service of a PVC sample. He compared the properties of accelerated aged materials with a 34 year old PVC material and making some assumptions produced a slight correlation between accelerated ageing and real life ageing. However, Jakubowicz et al (2001) in another work reports on some studies carried out in Germany and the USA, which could not find any correlation between artificial ageing and natural ageing. It is therefore possible to conclude accelerated tests do not predict about service life of materials.

The result of an accelerated test is often the more reliable the lesser the degree of acceleration and longer the testing period. This is particularly true if the test environment deviates in its chemical composition from that in the corresponding practical case. It is often necessary to strike some sort of balance between a reliable test result and a short testing time.

The consistency of the results produced by accelerated test has also been a matter of concern as indicated by Baldwin et al (1999), Rossini (1998) and Esmore et al (1973) as reported by Doppke (1983). It is therefore, believed that repeatability of tests with a high degree of fidelity is vital to produce reliable results. It is also considered that, for the results of accelerated tests to have significant validity, there must be evidence that a correlation exists with results in the actual environment of interest. Several researchers such as Ketcham et al (1985) suggest that the way to obtain such correlation is by conducting exposure tests in the natural environment. Figures 3.2 (a) and 3.2 (b) show the weathering testing in natural atmosphere at the Building Research Establishment (BRE).

Despite the above mentioned concerns, accelerated tests are still considered to be very valuable in the research and development phase of products for the useful information and data they provide about long term performance of investigated materials. Rossini (1998) reports that there are approximately 50 different salt spray tests being practised in the world which indicates the importance and widespread application of this test.

3.4 ACCELERATED TESTING OF WINDOWS

The comparative assessment of the three window frame materials (aluminium, PVC and timber) under common weathering conditions, is quite a complex process. This is mainly due to the fact that they are fundamentally different types of materials. Normally, accelerated tests are specifically designed for particular type of materials and are tested under certain conditions dependent on the intended use of the materials. There are a wide range of tests designed separately for different materials. Tests for polymers normally focus on their thermal performance. Tests for timber normally concentrate on their structural characteristics and biological degradation. Metals are normally tested for their mechanical properties and corrosion behaviour. These tests sometimes are quite sensitive in terms of materials being tested, for example, Albas (2000) reports that best prediction from accelerated tests is obtained if paint systems of the same type of binders are used. This sensitivity of tests up to minute level details of materials is also indicated by several ASTM tests. For example, G34-79 test described by Baboian (1995) is applicable only for 2XXX and 7XXX series alloys of aluminium.

There is no particularly defined accelerated test that could be applied to test materials that are different in characteristics, as in this case - Figures 3.3 (a), 3.3 (b), 3.3 (c) & 3.3 (d) show the four basic frame designs that were aimed to be studied. Literature reviewed could not provide any information to assess these different materials on a comparative scale. Accelerated testing of window frames, in itself, is quite a rare practice; only electrochromic windows have been reported to be tested under cyclic conditions as described by Lee et al (2001) and Tracy et al (1999). The American Society of Testing and Materials (ASTM) suggested that an optimum way to undertake the required comparative assessment would be to test the window frames in outdoor exposure for at least five years. This obviously, due to the limited time span of the project, did not match with the requirements and limitations of the work. Thus an accelerated testing programme was designed which focussed on separate frame materials.

Corrosion, in general, is a metallic phenomenon, therefore an immersion test was performed only for the aluminium samples (coated and uncoated). Dry-wet cyclic, humidity-temperature and salt spray tests were carried out on the whole range of materials since these testing environments are relevant to them all. Ultra-violet (UV) test was applied to all materials, however, its real significance was for organic materials (PVC and timber). Table 3.2 describes the specifications of the tests carried out. Salt spray, dry-wet cyclic and immersion tests were carried out at Otto-Von-Guericke University in Germany, as part of collaborative research activities, while UV and humidity-temperature tests were executed at Napier University.

3.4.1 Immersion test

This particular immersion test is designed to assess the corrosion tendency of aluminium samples.

3.4.1.1 Test conditions

Samples are immersed in a solution of 0.14M HCl and 0.26M NaCl for 24 hours at room temperature (22 C).

3.4.1.2 Test sample

The samples were, uncoated, anodised and powder coated aluminium specimens, each 40mm × 40mm × 3mm in size, obtained from the cladding profiles.

3.4.1.3 Results

After 24-hour immersion, the samples were dried and examined under an optical microscope. The observations made were as follows:

Uncoated aluminium; this showed extensive corrosion (Fig. 3.4).

Anodised aluminium; corrosion was observed on the machine cut (rough) edges of aluminium, as shown in Fig. 3.5.

Powder coated aluminium (from Nor-Dan); there was no evidence of corrosion and the integrity of the coating was excellent (Fig. 3.6).

Observations show that coated aluminium samples (powder coated and anodised) have remained unaffected under the corrosive solution except for the signs of corrosion on the machine cut edges of anodised samples. Figures 3.7 (a) and 3.7 (b) provide more evidence of the benefit of coatings.

3.4.2 Salt spray test

The oldest and most widely used standardised accelerated corrosion test is salt spray (Fog) testing, ASTM B 177, which was originally approved in the early 1900s. Over the years the concentration of the salt solution has ranged from 3.5 to 20%. The present 5% concentration was established in 1954. Salt solution is pumped into a nozzle where it meets a jet of humidified compressed air, forming a fine droplet spray. This test is used for general assessment of materials, coatings, surface treatments and is frequently quoted in specifications as a quality control test as described by Baldwin et al (1999) and Lyon et al (1992).

3 4 2 1 Test conditions

Samples were exposed to a jet of 5% NaCl solution for a duration of 96 hours, under controlled conditions inside the testing chamber.

3.4.2 2 Test samples

Test was carried out on different samples as given below:

Sample	Size
• Powder coated aluminium clad-timber	50mm×50mm×13mm
• Anodised aluminium-clad timber	50mm×50mm×13mm
• Uncoated aluminium	50mm×50mm×3mm
• PVC	50mm×50mm×6mm
• Timber	50mm×50mm×10mm

3.4.2.3 Results

After the test, the samples were observed visually and under low and high-power optical microscopes. There were corrosive attacks on the uncoated aluminium samples with signs of pitting corrosion being obvious on their surfaces. Painted and anodised aluminium-clad samples remained unaffected except for minor traces of corrosion on their unprotected edges. Timber underneath the aluminium cladding exhibited no deterioration. PVC samples also did not show any signs of degradation. However, the timber samples showed degradation with some crevices being observed as shown in Figs. 3.8 (a) and 3.8 (b).

3.4.3 Dry-wet cyclic test

The aim of this particular test was to observe the behaviour of materials under humidity, temperature and UV exposure, simulating the natural environmental conditions. Dry-wet cyclic testing is a more realistic way to perform accelerated testing than traditional steady state exposures, because the actual atmospheric exposure usually includes both wet and dry conditions. Brennan (1994) reports that the cyclic corrosion test yields results closer to outdoor observations.

3 4 3 1 Test conditions

The test was carried out for 96 hours, three cycles per hour. Each cycle involved 2 minutes of water spray, 15 minutes of UV radiation and 3 minutes of heating at 55°C.

3.4.3.2 Test samples

The samples tested were similar to those in salt spray test.

3.4.3.3 Results

After the test, the samples were examined visually and using low and high-power optical microscopes. There was pitting corrosion on both of the uncoated aluminium samples (Fig. 3.9) while the powder coated and anodised samples remained unaffected with no signs of corrosion. There were no degradation signs found on the PVC sample. The timber samples degraded due to the affects of moisture and heat – Figs. 3.10 (a) and 3.10 (b) show warping of the timber samples.

3.4.4 Humidity-temperature test

This test was carried out to evaluate the performance of materials under high humidity and temperature which are amongst the main environmental factors effecting all types of materials.

3.4.4.1 Test conditions

The test cycle comprised 24 h at 60°C and 88% relative humidity, followed by 24 h at 60 C heating. The test was carried out in a test chamber for 144 hours and consisted of 3 complete cycles of 48 hours each.

3.4.4.2 Test samples

In this test four complete window units (Fig. 3.11), of the size 45cm × 45 cm, were tested. These windows were of following types;

- Powder coated aluminium-clad timber
- Anodised aluminium-clad timber
- Painted timber
- Timber without paint

In addition, the following samples were tested - each having cross section of 10 cm × 10 cm, but with various thickness.

- Powder coated al clad timber
- Uncoated aluminium
- PVC
- Timber

- Sample from a used (12 years old) PVC window profiles
- Sample from a used (35 years old) timber window profiles

3 4 4 3 Results

After completion of the te t, the samples were observed visually as well as under optical microscopes. Timber windows during this test, did not reveal any crevices or warping characteristics (unlike salt spray and dry-wet cyclic tests). There was a minor change in the colour of the unpainted timber windows. Painted windows however, did not exhibit any colour change. The aluminium clad timber windows remained completely unaffected by this test. Timber underneath cladding was also unaffected. The greatest impact of this test was observed on the PVC samples; they lost their appearance (Fig. 3.12) unlike the salt spray and dry-wet cyclic test. Uncoated aluminium samples experienced some corrosion but powder coated and anodised aluminium remained unaffected.

The older timber samples exhibited moisture (Fig. 3.13)and heating impacts resulting in a change of colour and making already existing cracks more pronounced.

It was observed that ironmongery of the windows exhibited impacts of the test conditions. Oxidation and corrosive signs were obvious in all windows (Figs. 3.4 (a), 3.14 (b), 3.14 (c) and 3.14 (d)).

3.4.5 Ultra-violet test

Ultra-violet radiation is one of the most critical environmental factors that deteriorates materials (as discussed earlier in section 2.2.1). This test aimed to study the behaviour of materials under exposed UV and humid conditions, simulating the solar radiation and moisture (in the form of rain or dew). Fluorescent UV lamps are usually employed to simulate the solar exposure. Fluorescent UV lamps are usually categorised as UV-A or UV-B lamps, depending on the region into which most of their output falls. The UV spectrum is divided into three regions:

- UV A Region, wavelength; 315-4 0 nanometers
- UV-B Region, wavelength; 280-315 nanometers
- UV-C Region, wavelength; below 280 nanometers

In this test UV B lamps were employed. The UV-B region includes the shortest wavelength found in sunlight at the earth's surface. UV-B radiation is responsible for most of the degradation by solar radiation e pecial y for polymers.

3.4 5.1 Test conditions

The test was conducted over 2 weeks consisting of alternating cycles of 4 hours of exposure to UV-B lamps at 45°C and 4 hours of condensation at 50 C, under controlled conditions inside the UV chamber.

3.4.5.2 Test samples

- Powder coated aluminium-clad timber
- Anodised aluminium-clad timber
- Unpainted timber
- Painted timber
- Uncoated aluminium
- PVC
- Timber

Samples were of the size 4 cm × 4 cm cross sections with varying thickness.

3 4 5.3 Results

After completion of the test, the specimens were observed visually. The PVC sample was greatly affected by the ultraviolet light. Its white colour had turned to dark brown (Fig. 3.15). Unpainted timber samples also showed signs of degradation – their colour had slightly faded (Fig. 3.16). The painted timber samples however showed no colour change. Remaining samples, uncoated and coated aluminium remained unaffected as expected. There were no signs of any sort of degradation on the timber underneath the aluminium cladding.

3.5 TEST RESULTS AND DISCUSSION

The results of tests have shown the respective tendencies of window frames to receive environmental impacts. The following conclusions emerge from the results of these tests.

- Immersion test that was only for the aluminium windows has revealed the importance of surface treatments. The corrosive solution in the immersion test caused pitting corrosion on the surface of uncoated aluminium samples. The corrosive attack on the unprotected edges of anodised aluminium samples could have been avoided if the edges were well prepared. Powder coated samples remained totally unaffected by the corrosive solution.

- Salt spray test showed degradation in uncoated aluminium and timber samples. Uncoated aluminium samples experienced pitting corrosion while timber samples got crevice openings. Crevices produced in the timber samples as a result of salt spray testing, might be due to sodium chloride which can cause defibrisation or rupturing of fibres at and near the exposed surface. Defiberization is caused by the formation of salt crystals in the timber cells. When these crystals enlarge, they rupture the cell walls causing openings to develop in timber. Although this is typically limited to degradation at the surface, it is possible for the degradation to extend inwards around 25-mm or more if the process is allowed to continue for extended periods of time. The crevices produced however, fully recovered within 24-36 hours, after the timber had dried. Remaining samples, i.e. powder coated aluminium, anodised aluminium and PVC did not experience any degradation.

- The results of the dry-wet cyclic test have shown that timber samples experienced degradation they got warped. The warping of timber samples represents the phenomenon that a change in moisture content is accompanied by a corresponding changes in dimension; a decrease in moisture results in shrinkage, and an increase in moisture results in swelling. Again, the warped timber samples regained their original shape after about 48 hours when they got dried. The changes in materials could have been more evident for a longer duration of test. UV and temperature exposure in particular were not intensive enough to affect other materials. There was pitting corrosion on uncoated aluminium samples while the powder coated and anodised samples remained unaffected with no signs of corrosion. There were no degradation signs found on the PVC sample.

- In humidity-temperature test, timber and PVC in general did not show any significant sensitivity towards relative humidity (moisture spray). High temperature however, has been a factor considerably affecting the PVC samples in the form of discoloration. It is thought that this discoloration was due to the continuous exposure of PVC to high temperature for longer times. Unpainted timber received only a minor colour fading. Timber windows during this test, did not reveal any crevices or warping characteristics (unlike salt spray and dry-wet cyclic tests). This was due to the fact that the timber samples used in the salt spray and dry wet cyclic tests were unrestrained and of small size (5cm ×5cm). The untreated surfaces of these samples got the impacts of severe conditions and yielded crevices and warping in the respective tests. Behaviour of timber windows in humidity-temperature test shows that they do not undergo such environmental degradation due to moisture and temperature; the crevices and warping observed in salt spray and dry wet cyclic test respectively, were due to specific nature of test samples (due to their very small size and edges having not been treated); they were not true resemblance of the actual window profiles. The impacts of humidity on timber windows, however, can not be ruled out completely; moisture, in the form of humidity, rain or dew plays its role in the degradation of timber in real life, but not to the extent shown in salt spray and dry-wet cyclic tests. Painted timber windows have shown resistance against both the temperature and humidity. This shows that the surface treatment and coatings on timber retard the rate at which moisture uptake occurs, thereby moderating the response of the timber to changing environmental conditions. Aluminium clad timber windows, have remained unaffected both by the humidity and temperature.

- UV test results indicate that PVC windows are more likely to be affected by UV radiation. UV radiation damages the chemical bonds of PVC. The resulting colour changing process is defined as dehydrochlorination which is characterised by the formation of Polyene sequence. Results also indicate that the sunlight affects PVC significantly more as compared to timber, because the colour change of timber is not severe enough to affect its appearance or functionality. Unpainted timber windows received minor impacts in the form of colour change. The colour change of timber occurs because the sunlight (especially ultraviolet light) decomposes the lignin as well as the organic materials (cellulose and hemicellulose). Painted timber windows did not experience any discoloration, which shows that surface treatment reduces the impacts of UV. Aluminium and aluminium clad timber windows also did not exhibit any degradation in the form of colour change.

- The results of the accelerated testing provide valuable information regarding the behaviour of studied windows under the natural environment, since, the conditions produced in tests were simulating the usual environmental factors the windows come across in real life. As discussed above, results have indicated the probabilities of uncoated aluminium and PVC windows getting deteriorated in the form of corrosion and discoloration respectively. Timber windows have also shown tendency of receiving impacts of UV and high temperature. Aluminium clad timber in general remained resistant against the applied environmental conditions in all the tests. They have also appeared to possess better overall weathering performance as compared to aluminium, PVC and timber windows. Cladding acts like a shield protecting the underneath timber from environmental conditions. With the help of proper surface treatment, i.e., anodising or powder coating, aluminium exhibits good resistance against corrosive conditions.

In the tests carried out within the present context, the limitations with the size of test samples are assumed not to make any significant difference in their behaviour than if complete windows were tested. The only deviation noted is with the small timber samples as discussed above.

In these tests, samples were not mechanically tested because structural breakdown of window frames is a very rare phenomenon. Weathering produced on window frames; Corrosion of aluminium, paint fading of timber and discoloration of PVC can easily be studied by the techniques applied i.e., visual and microscopic observation.

An important point to be remembered when assessing the results is that the conditions in testing chambers are sometimes so harsh that they generate excessive environmental stresses on materials which can produce changes in materials that are not observed on a short term basis (in the real life). For example, the great deal of discoloration of PVC in UV test might be an exaggerated picture of real life situation, although, discoloration of PVC windows does occur in real life upon exposure to high temperature and UV radiation. Similarly, uncoated aluminium does get corroded in real life but not to the extent shown in present test results. However, in both the above stated examples, the lesson learnt from the test results is the confirmation of respective degradation tendencies of PVC and aluminium windows, the time period and intensity of degradation remaining as the interpretable issue. This typical correlation of accelerated testing with the real life exposure has been reported by several researchers. For example, Damborenea et al (1995) carried out accelerated testing of aluminium alloys and compared the results with those obtained after 2 years of outdoor exposure. The comparison showed corrosion occurred both in the accelerated and outdoor testing; however, the accelerated test produced a greater degree of corrosion. It is therefore important to strike a balance between the results of accelerated tests and the real life exposure.

In the weathering of windows, their positioning and direction of exposure play an important role. It is quite often found that different portions of the same window frame receive environmental impacts in various degrees depending upon their position; being under the shade or exposed to severe humidity and wind flux. For example, as shown in Fig 2.3 (a) in chapter 2, the bottom part of the timber frame that is the opening side of frame has deteriorated more than the top. Similarly windows directly exposed to sun, coastal wind or industrial pollution waves have higher tendency to get affected than those which are not directly facing these exposures. This phenomenon is associated with accelerated testing as well - the positioning of samples against the flux of applied conditions in the test chambers affect the results. For example, Doppke et al (1983) report that in case of salt spray test, vertical positioning of samples cause less corrosion due to fast solution run off and horizontal positioning cause more corrosion because of longer salt solution contact. It is therefore important to take into account the positioning of samples while interpreting the results.

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Fig. 3.1 Corrosion test chamber

Fig. 3.2 (a) Different designs of windows being tested under natural exposure

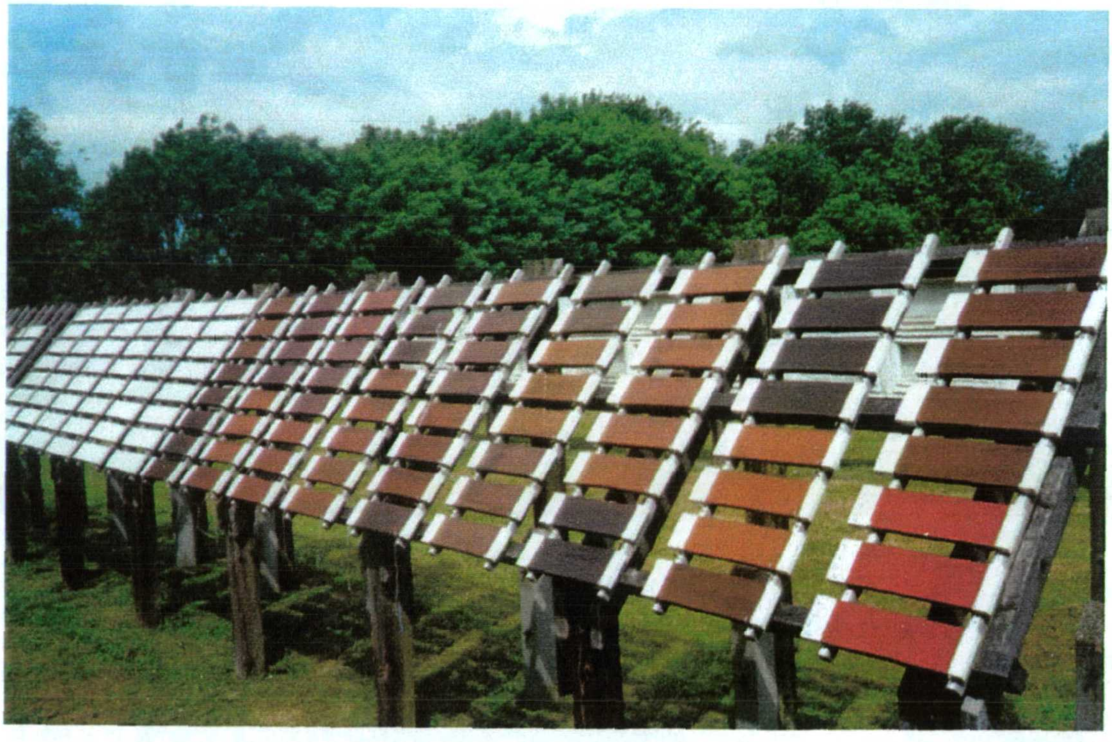

Fig. 3.2 (b) Different surface coatings on windows being tested under natural exposure

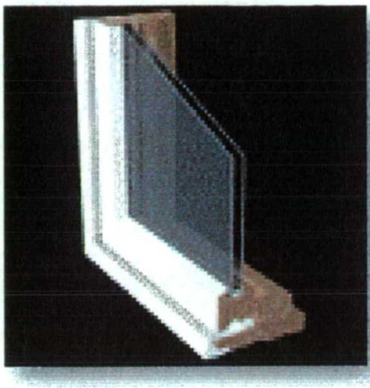

Fig. 3.2 (a) Aluminium-clad timber window cross section

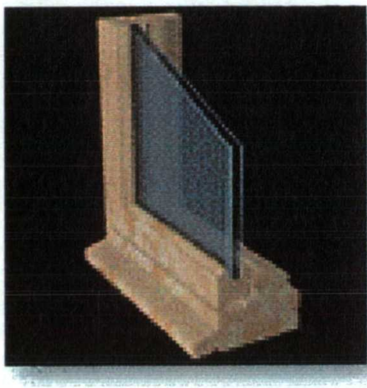

Fig. 3.2 (b) timber window cross section

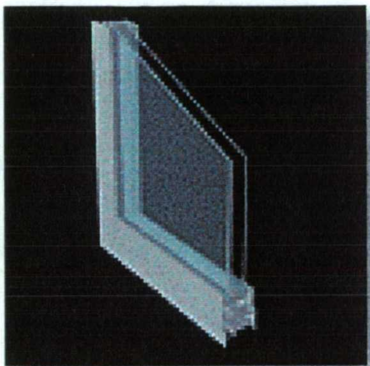

Fig. 3. 2 (c) Aluminium window cross section

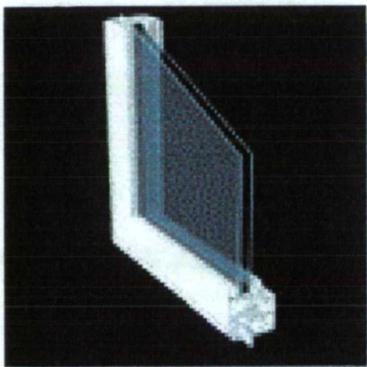

Fig. 3.2 (d) PVC window cross section

Fig. 3.3 Cross sectional views of tested windows types

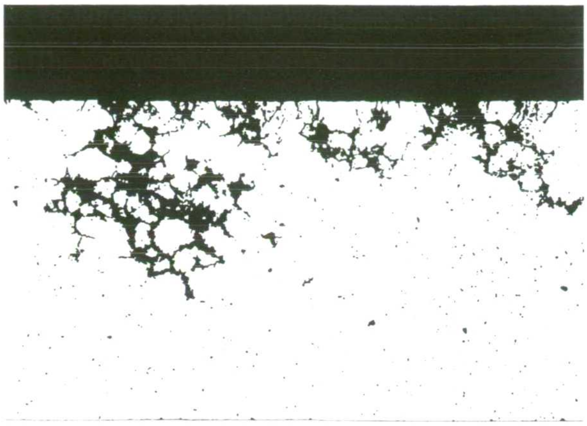

Fig. 3.4 Uncoated aluminium sample showing corrosion @ magnification of 100

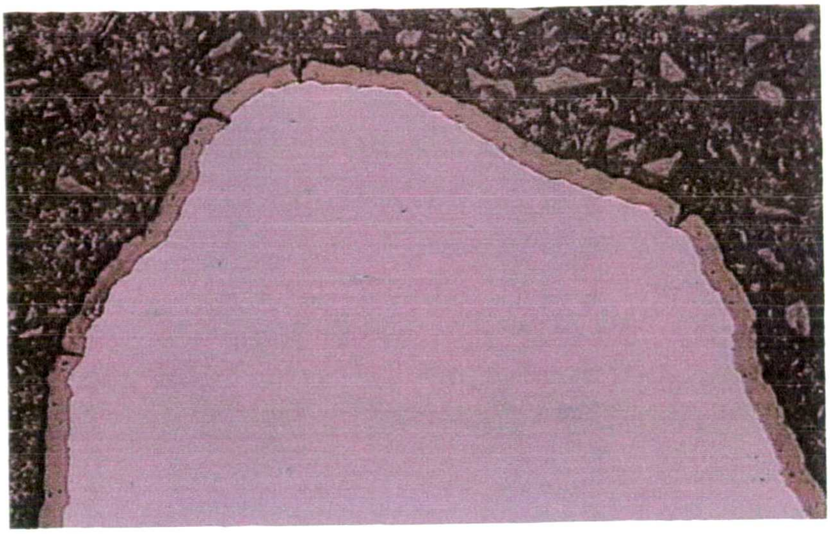

Fig.3.5 Anodised aluminium samples showing breaks in the anodised layer due to corrosion @ magnification of 100

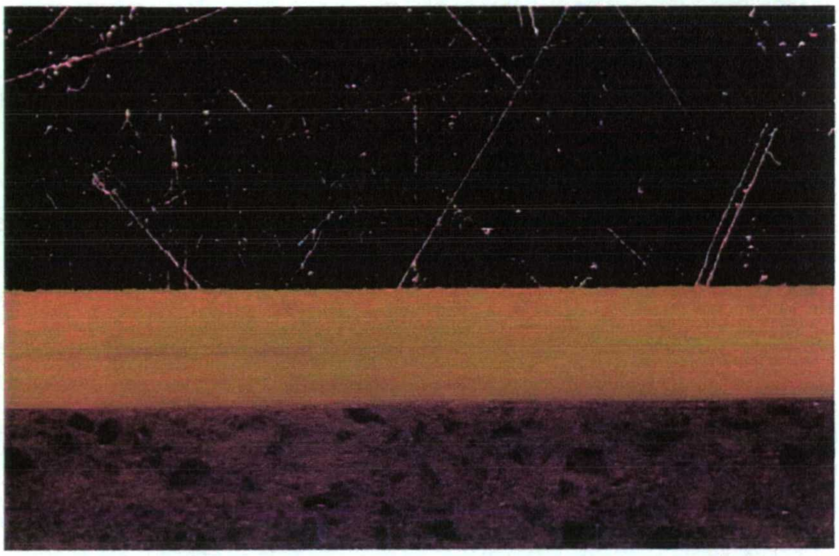

Fig. 3.6 Powder painted aluminium sample, with no sign of any damage to coated layer @ magnification of 100

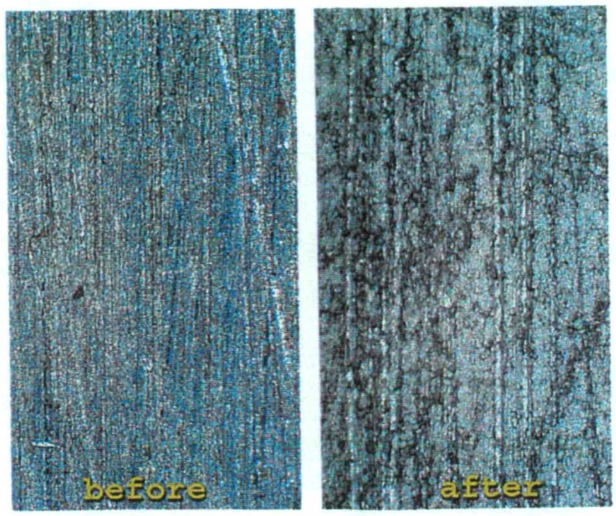

Fig. 3.7 (a) Uncoated aluminium showing corrosion after the immersion test

Fig. 3.7 (b) Anodised aluminium sample, without and after the test, showing no signs of corrosion

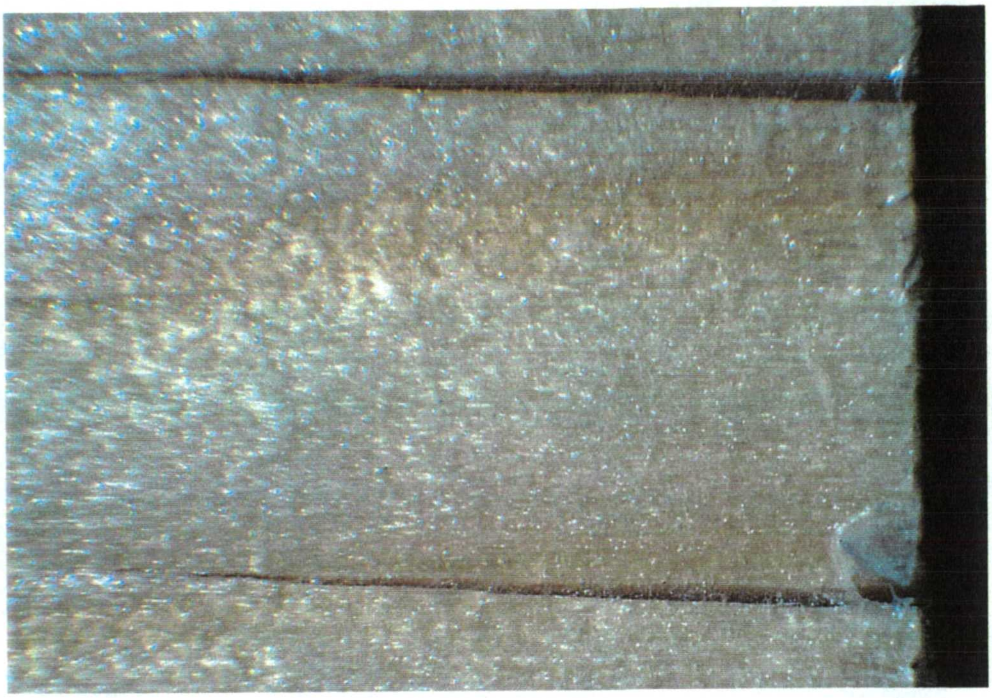

Fig. 3.8 Crevices produced in timber samples as a result of salt spray test

Fig. 3. 9 Pitting corrosion in uncaoted aluminium after the salt spray test

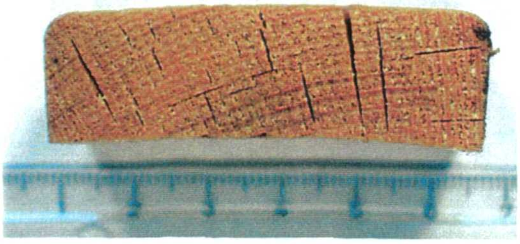

Fig. 3.10 (a) Dry-wet cyclic test produced warping in timber sample

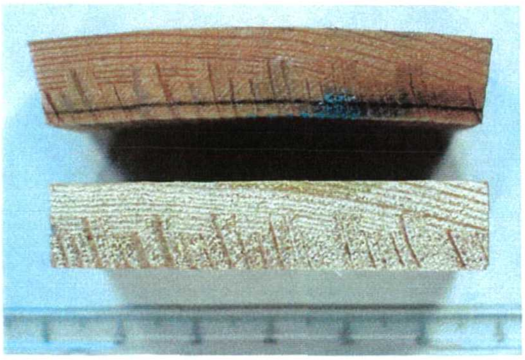

Fig. 3.10 (b) Dry-wet cyclic test - tested (top) and untested (bottom) samples highlighting the warping

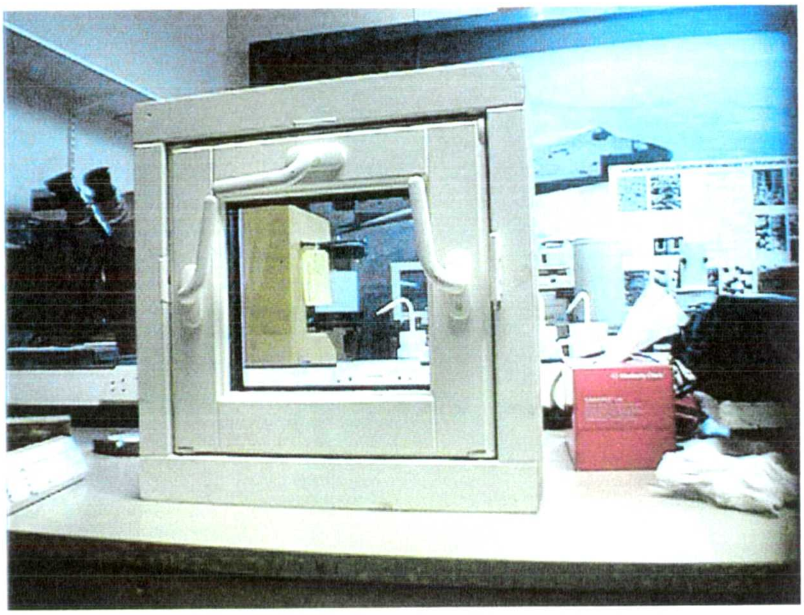

Fig. 3.11 One of the windows that were tested in humidity-temperature test

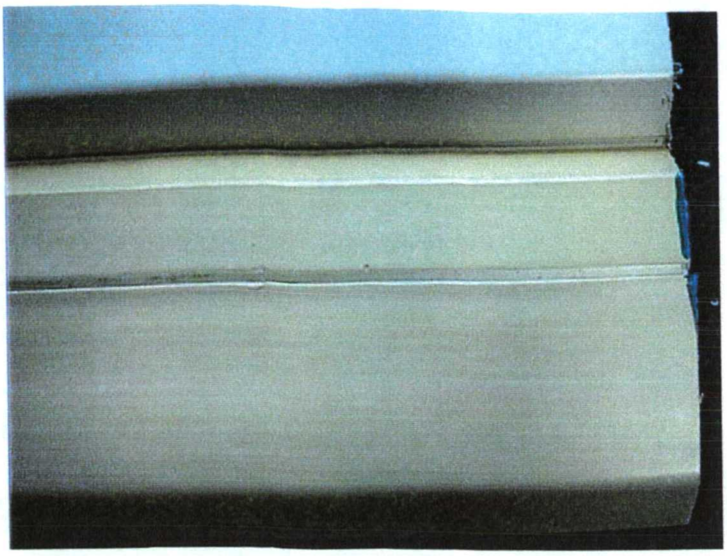

Fig. 3.12 Comparison of PVC samples showing discoloration
after humidity-temperature test– tested (bottom) & untested (top)
(Original figure is in colour)

Fig. 3.13 Decomposed brown-coloured lignin leached out of timber due to impacts of moisture and heat

Fig. 3.14 (a) Ironmonger of window before the humidity/temp test

Fig. 3.14 (b)Corrosion is quite visible after the humidity/temp test

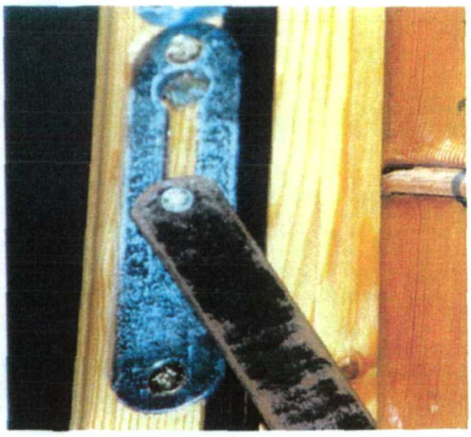

Fig. 3.14 (c) Oxidation of ironmonger of timber window under the humidity/temperature test

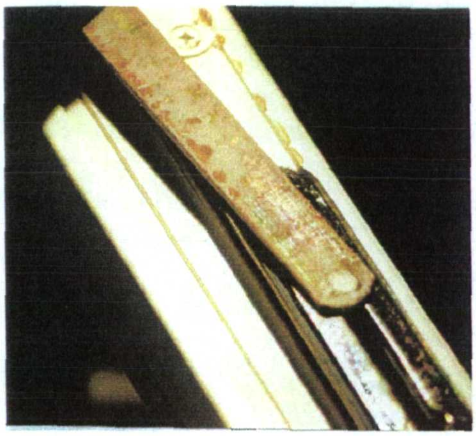

Fig. 3.14 (d) Corrosion of ironmonger under the severe humidity/temp conditions

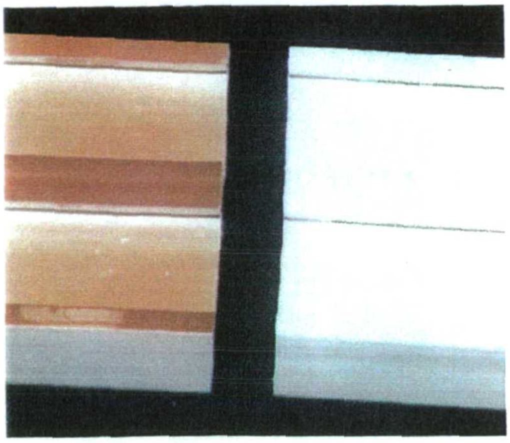

Fig. 3.15 Discoloration of PVC under UV test – tested (left) and untested sample (right)

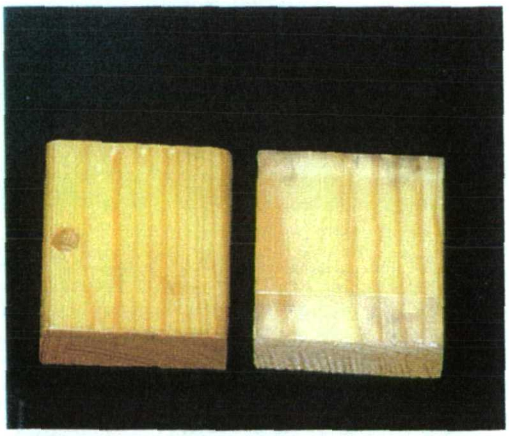

Fig. 3.16 Slight discoloration of timber under UV test – timber underneath the cladding that retained its colour, and the sample exposed to UV (right)

Table 3.1 Some standard ASTM tests

Test	**Specifications**
ASTM B 117	Method of Salt Spray(Fog) Testing
ASTM D 2247	Practice for Testing Coated Metal Specimens at 100° RH
ASTM G 1	Practice for, Preparing, Cleaning, and Evaluating Corrosion Test Specimens
ASTM G 46	Practice for Examination and Evaluation of Pitting Corrosion
ASTM G 50	Practice for conducting Atmospheric Corrosion Tests on Metals
ASTM G 60	Method of Conducting Cyclic humidity Test
ASTM G 85	Practice for Modified Salt-Spray (Fog) Testing
ASTM G 87	Practice for conducting Moist SO_2 Tests

Table 3.2 Accelerated test carried out and their specification

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.

CHAPTER 4: ENERGY AND ENVIRONMENTAL IMPACT ASSESSMENT OF AL-CLAD TIMBER WINDOWS

4.1 INTRODUCTION

Every system, product or activity brings along its associated environmental impacts with it, at every stage of its life; whether it is the consumption of natural resources or generation of pollutants and wastes, as shown in Fig. 4.1. In the last decade of the twentieth century and with the advent of twenty-first century there is an increased concern that mankind must utilise natural resources in a sustainable way in order to secure the future of coming generations. To achieve this, it is necessary to use these resources wisely and in a responsible way. Life cycle assessment (LCA) is a very helpful tool in this regard, providing a material and energy balance over the entire life of a material, product or service, determining its interaction with its environment and assessing its impact on the environment.

Energy characterisation is fundamental to an LCA in that energy utilisation, in addition to being a significant resource requirement, contributes significantly to environmental burdens across the entire life cycle. Consequently one common measure of environmental burden is energy use itself. The energy requirement does not in itself measure environmental impact; it is however useful as a proxy for the level of stress that energy use may cause in the environment. Each form of commercial energy whether utilised as direct fuel, as electricity or in transportation, exhibits a life cycle of its own and includes mining, refining, conversion and distribution.

A product, system or service can generally be evaluated for its environmental behaviour on the basis of the degree of its intensity towards the following scales:

- Emissions to air
- Emissions to water
- Global warming potential
- Acid deposition potential
- Depletion of reserves
- Use of fossil fuels
- Use of renewable energy
- Total energy demand
- Output of solid waste

This chapter provides the assessment of some of the basic features of the LCA; energy and environmental impacts assessment. This study does not address the packaging and transportation involved. The data and information presented here were acquired during a survey of the Nor-Dan windows production plant, and the powder coating unit in Norway. For this purpose, embodied energy of the window contents such as aluminium, timber, glass, filling gases has been estimated. Powder coating manufacturing and assembling processes have also been investigated. An energy evaluation has also been carried out for a standard (1 2 m × 1 2m) double glazed aluminium clad timber window with Argon (Ar), Krypton (Kr) and Xenon (Xe) infill gases.

4.2 LIFE CYCLE ASSESSMENT

Life cycle assessment is defined as: 'A process to evaluate the environmental burdens associated with a product system, or activity by identifying and quantitatively or qualitatively describing the energy and materials used, and wastes released to the environment, and to assess the impacts of the energy. The assessment includes the entire life cycle of the product or activity, encompassing, extracting and processing the raw materials ; manufacturing; distribution; use; reuse; maintenance; recycling and final disposal; and all transportation involved (Lindfors, 1995 as reported by Edwards 1996)

ISO 14040 (1997) defines LCA as

'LCA is a technique for assessing the potential environmental aspects associated with a product (or service) by compiling an inventory of relevant inputs and outputs, evaluating the potential environmental impacts associated with these inputs and outputs, and interpreting the results of the inventory and impact phases in relation to the objectives of the study'.

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. The results of an LCA depend on the assumptions made and the system boundaries. Figure 4.2 by Davis (1998) described the framework of typical LCA.

There are the following four interactive steps necessary for a complete life cycle study, as shown in Fig. 4.3;

- Planning
- Inventory analysis
- Impact assessment
- Improvement analysis

These are discussed in detail as following.

4.2.1 Planning

In a LCA framework, goals and objectives are first defined including the investigation boundaries, breadth and depth of study. LCA can be used for many different purposes such as new product development, identification of harmful stages in product life cycle, comparison of two products, allocation of product resources, categorising the research and development needs or aggregation of total environmental burdens. System limitations may include such considerations as data availability, future environmental effects and technology development requirements.

4.2.2 Inventory analysis

Inventory analysis is the quantitative input/output account of the product system. This is a measure of all matter that crosses the boundary defined in the goals-defining and scoping phase. Energy, raw material, air emissions, water-borne effluent and solid waste are examined and measured.

4.2.3 Impact assessment

Impact assessment focuses on how the product affects the environment. This requires a qualitative and quantitative approach to analyse how raw material use, energy generation, water production, effluent output, air emission and solid waste affect the environment. Impact assessment can be divided into three sub-phases:

1. Classification, where material and energy inputs and outputs are classified into impact categories.
2. Characterisation, where the contributions to each impact category are assessed by quantitative or qualitative methods.
3. Valuation, where the contribution of each impact category is addressed and related to each other, and the total impact assessed.

4.2.4 Improvement analysis

This involves making improvements to reduce environmental burdens and this requires taking an objective view of the entire life cycle and assessing the impact that changes would have on the environment. This may result in product design changes, raw material substitutions, manufacturing process changes, or improved waste management facilities.

4.3 ALUMINIUM CLADDING ON WINDOWS

Aluminium cladding is the covering of the exterior surface of the frame and sash of a window with aluminium profiles, for better protection against weathering effects. In cladding, a sheet of aluminium (about 3 mm in thickness) is attached on the exterior surface of the window frame, with a gap of about 6 mm being maintained between the cladding and timber surface to allow for optimum drainage and drying of the wood after, for example, rain and snow; as shown in Figs. 4.4(a) and 4.4(b). It keeps the wood underneath protected from environmental degradation factors and helps increasing the overall service life of the window. Cladding has an aesthetic aspect as well, since it is available in a wide range of colours providing a cosmetic touch to the exterior of windows. Another important role of cladding is its economical contribution by cutting down the maintenance cost of the windows (as described in detail in section 5.3.5). Aluminium, due to its favourable characteristics for use in construction, as discussed in section 2.3, is the common cladding material choice for timber windows. Already possessing good corrosion resistance properties, aluminium profiles, are furthermore surface treated to attain even better protection against weathering conditions. Powder coating and anodising are the common surface treatments applied on aluminium profiles. The present work, however, was to investigate the powder coated aluminium cladding.

4.3.1 Aluminium alloy 6063

The aluminium used for cladding windows is the 6XXX series alloy, aluminium 6063. This alloy contains Silicon (0.4%) and Magnesium (0.7%) besides the fundamental aluminium constituent. The alloy can be readily extruded, possess good formability and can be readily welded and anodised. Alloy 6063 has good resistance to atmospheric corrosion and is the most commonly used alloy for extruded shapes for windows. Table 4.1 shows physical properties of 6063 alloy.

4.3.2 Powder coating of aluminium cladding

Aluminium cladding profiles are powder coated for better protection against corrosion and other weathering impacts. Aluminium profiles require a good degree of pre-treatment prior to powder coating because proper surface cleaning and treatment is essential for good adhesion and durability of the applied coatings (Davey, 1998). The pre-treatment cycle purges trapped moisture, oils and gasses that cause surface contamination.

The most common pre-treatment in powder coating involves the application of zinc phosphate conversion coatings with the phosphates acting to form a coating of metal phosphate crystals on the metal surface. These crystals are porous, allowing powder to soak-in and produce an exceptionally good bond. In addition, the phosphate layer acts to insulate a variety of "electrochemical corrosion cells" present in the metal, and formed by peaks and valleys in the metal surface and by stress. Insulating these cells with a metal phosphate contributes significantly to corrosion resistance, as reported by Adams (1998) and Grubbs et al (1999).

The pre-treatment process of aluminium profiles consists of dipping profiles into a series of tanks containing chemicals and clean water, and it can be summarised as follows:

1. Degreasing
    - Dipping in highly alkaline soap water
    - Rinsing in clean water
2. Pickling
    - Acidic pickling
    - Rinsing with clean water
    - Activating
3. Zinc phosphating
    - Dipping in zinc phosphate acid
    - Rinsing in clean water
    - Passivating
4. Drying; in heating chamber at approximately 85°C

The coating powder comprises four basic components: resins, pigments, additives and extenders. The resins include epoxies, polyesters, acrylic or urethane base. Pigments provide colour and hiding properties. Extenders give such properties as low gloss flow, edge covering, etc. Additives are used in very small quantities to help reduce or extend cure time and temperature, improve or reduce flow, and raise or lower gloss, among other effects.

The powder is applied by an electrostatic spray technique. The powder is positively charged as it leaves the gun to be deposited on an oppositely charged work piece (profiles). The powder layer applied on aluminium profiles is almost 80-90 µm thick. After the powder is applied, it must be heated, during which it begins to wet and flow on, and into rough imperfections on the surface and bond it. For this, profiles are then taken to a furnace that melts the powder which was still in the dry powdered form and not bonded with the profiles. The temperature in the furnace is kept at the critical range of the powder - in this case 85-115 °C. This curing process is both time and temperature dependent. The aluminium profiles are heated in furnace for a time period of 10 minutes, which is sufficient for their curing. When profiles cool down, the result is a tough corrosion resistant coating that has almost been fused onto the surface. Figure 4.5 shows a complete sequential sketch of the powder coating process.

4.4 ENERGY ANALYSIS OF THE STANDARD NOR-DAN ALUMINIUM-CLAD WINDOW

4.4.1 Total energy involved in cladding

The energy involved in aluminium cladding can be categorised into three main areas; embodied energy of aluminium metal used, energy associated with powder coating and energy consumed during profiles cutting in the windows assembly unit.

4.4 1.1 Aluminium profiles

Energy content of aluminium, as reported by different research findings varies. This variation might be because of the differences of the respective frameworks i.e., nature and boundaries of the investigations carried out; any analysis carried out depends upon the details and defined boundaries of the investigation (the planning phase of the LCA) which should have to be acknowledged when concluding the results. Sometimes the variation of the results of different studies is quite significant, for example, for embodied energy of aluminium, Buchanan (1993) provides a value of 135 MJ/kg and Saito (1995) as reported by Weir (1996) provides a value of 502.5 MJ/kg. Haupin (1987) has provided a detailed breakdown of energy content of aluminium and provided a value of 231.9 MJ/kg, as shown in Table 4.2. Berge (2001) reached a value of 184 MJ/kg, taking into account 50% recycled aluminium. Young at al (1994 &1995) reports the values for both primary and secondary aluminium equal to 225MJ/kg and 50MJ/kg respectively, referring to a number of research works including Houghton et al (1990 & 1992), Yoshiki et al (1993) and Stobart (1986). Having studied the findings of these research works, the detailed analysis reported by Haupin (1987), is considered to be suitable for the current work. Berge (2001) reports that the production of aluminium in northern Europe consumes less than one third (31.5%) of the energy required to produce aluminium in central Europe. Following this assessment, the energy content of primary aluminium production in northern Europe is 73 MJ/kg. The present research work is based on windows produced in Norway, for which aluminium used, is obtained from Sweden. The value of aluminium energy content are therefore, the one implied for northern Europe, i.e., 73 MJ per kg of primary aluminium.

O'Connor (2000) and IAI report that the production of recycled aluminium requires about 5% of the energy needed for primary aluminium production from ore while Berge (2001) states that recycled aluminium consumes 7 % of the amount required for primary aluminium production. Since Berge is an independent source therefore figures provided by him are used in current work. UNIDO (1989) quotes that about 27% of world's total aluminium production comes as secondary aluminium after being recycled. Considering the allowance for secondary aluminium, the embodied energy of aluminium used in present work is calculated to be 54.7 MJ Kg.

The amount of aluminium cladding fixed to one window is equal to 3.62 Kg and allowing for a wastage of 8% during profile cutting process, the total amount of aluminium used is estimated to be 3.91Kg. This provides a total embodied energy of 214 MJ for aluminium profiles used in cladding the standard window.

4 4.1.2 Energy analysis of powder coating

The main areas of interest in powder coating unit, relevant to this research work, are energy contents of powering the process and the powder used in coating. A number of different chemicals are used in small quantities in pre-treatment of the profiles. Embodied energy data were not available for these chemicals, however, as discussed in next section, the embodied energy of these chemicals is small enough to be of any significance when considering the whole picture of energy analysis of the window cladding. This study, therefore, does not address the embodied energy of chemicals. Rest of the data were collected and analysed for the years 1998, 1999 and for the first 4 months of the year 2000. The processes involved were observed, direct calculations were made, interviews were held with key personnel from different departments, past records were investigated and suppliers of materials were also contacted for required information. Here the energy analysis is made on the basis of performance of the unit during the whole year 1999.

Total power consumed by the powder coating unit in the year 1999 is equal to 7698.1 GJ. This is the power used in the whole production unit, covering energy used in the heat treatment, powder chamber, furnace, conveyors, water treatment unit, air exhaust systems and all other forms of energy involved in services and administration facilities. Over the studied period, the total amount of power consumption for work on aluminium profiles was 2155.5 GJ. The total number of profiles coated during this period amounted to 177125. All these profiles were 6 meters long but are classified in different categories according to their cross sectional sizes and designs, as required for different types of windows. These processed profiles have the gross weight of 313009kg. The power consumption can be therefore expressed as 6.89 MJ Kg. The amount of powder used for aluminium profiles is 16403kg, that provides the powder consumption for coating each kg of profiles equal to 0.05kg. The embodied energy of powder is estimated as 0.66 MJ/kg. Total mass of aluminium cladding fixed to the standard analysed window is 3.91 kg, that would require the energy consumption of 26.92 MJ, and 0.135 MJ for the power load and powder used, respectively, as shown in Table 4.3.

4.4.1.3 Cladding Profiles cutting

Aluminium profiles after having been powder coated, arrive at the windows production plant. There is a large hall for cutting cladding profiling, containing various saw and profile cutting machines. The total load power of this aluminium processing unit is estimated as 12kW. This unit works on average 7 hours a day, and 230 days a year. This gives an annual energy consumption of 69.952GJ. For total number of 29433 windows produced in a year. This yields the energy consumption for each widow equal to 2.363 MJ.

Powder coating energy has been already discussed that is 27 MJ for the whole window. The total embodied energy of cladding a window is thus evaluated to be 243.4 MJ as shown in Table 4.4.

In uncladded timber windows, aluminium strips are used as a boundary shield around glazing and are also fitted along the bottom of the sash to protect the timber from water penetration. In the presence of cladding these outer protections are not required. The mass of aluminium used as outer protection is 1.45kg, which is not needed in the presence of aluminium cladding. Therefore in cladding a window, the extra amount of aluminium used is in fact 2.46 kg, that contains embodied energy of 134.6 MJ.

Considering the powder coating energy consumption of 27 MJ, the extra energy associated with cladding is thus, 161.6 MJ.

The energy contents of powder used are less than 1% of the energy consumed in the form of power during the powder coating. Further, the estimated energy consumed in the whole powder coating process is less than 4% of the total embodied energy of aluminium cladding. Therefore the embodied energy of chemicals consumed in powder coating process, is of minimal importance when considering the entire window.

4.4.2 Glazing unit

Double glazed window's glazing unit basically comprises of glass and inert gas (optional) besides rubber sealing and spacer etc. Glass and inert gases are discussed as under.

4 4.2.1 Glass

The production of glass is an energy intensive process. Glass has an estimated embodied energy of 13 MJ per kg, as extracted from the work of West et al (1994). The mass of glass required for the investigated double glazed unit is 21.2 kg in the finished product. A small amount of material is wasted due to breakages and small offcuts which cannot be used. This amounts to approximately 5.5% of the total glass utilised. Taking this into account means that the average glass consumption for one unit is 22.26 kg, having an energy content of 289 MJ.

4 4.2.2 Inert infill gases

Inert infill gas or air is used in between the two glass layers of the double glazed windows to enhance the thermal resistance of the windows. Normally air or Argon gas is used in glazing cavity although Krypton and Xenon gases can also be used. The cavity gap between the two layers of glass depends upon the infill gas used. As the molecular weight of the gas increases, a smaller cavity gap is required, since the thermal conductivity drops with the increase of molecular weight.

The cavity gap between the glazing layers is maintained as 20 mm, 16 mm, 12 mm and 8 mm, for Air Argon, Krypton and Xenon respectively. The amount of infill gases required to fill the respective cavities is 22 litres, 17.6 litres, 13.2 litres and 8.8 litres. According to the work done by Muneer et al (1995) the estimated energy required to produce Argon, Krypton and Xenon to fill their respective cavity gaps is 0.01MJ, 502.8 MJ, and 4.50 GJ.

4.4.3 Timber

Softwoods are fast growing, easy to process and provide good surface finishes. They also have a long service life and good durability. The frame and sash of the windows investigated are made of softwood, mainly Baltic Redwood and Pine, but other types of timbers are also used. Nor-Dan carries out further treatment processes to increase the resistance of wood against warp, rot, fungi and insect attack. The treatment carried out is vacuum impregnation which increases resistance of timber against biological attacks and preserve it for a longer service life.

There are many uses for timber, requiring different treatment processes with associated varying energy contents. As the methods for evaluating the energy content of materials are numerous and varied depending upon the planning phase and working boundaries, there exists variation in the work done towards energy evaluation of softwood in different studies. West (1994) reports embodied energy of softwood to be equal to 2.6 GJ/m^3.

Allowing for the waste within the window production process, for the window analysed in this research, a total mass of 37 Kg of timber is required (frame 14.94 Kg, sash10.01 Kg, waste 12.05 Kg). The density of softwood varies greatly, according to the water content in the timber, but an average of 500 Kg/m^3 is used. This gives an energy content for timber component, exclusive of machining, of 192 MJ.

For sash sections timber is passed through a laminating process where two or three sections of timber are glued and compressed together. The estimated energy content of glue used in the analysed window is 2.94MJ, which brings the total embodied energy of timber sash and frame in the whole window to an amount of 195.3MJ.

4.4.4 Other aluminium components used

Aluminium is used in the window for other functions as well besides the cladding. It is used as glazing unit spacer, in frame ventilation and in components used in window adjusting mechanism. Mass and energy contents of these parts are given in Table 4.5.

4.4.5 Manufacturing and assembly

Energy involved in the manufacture and assembly of windows involves four main areas; aluminium processing, wood processing, sealed glazing production and factory services. The energy used in the manufacturing /processing of aluminium has been discussed earlier in section 4.4.1.3 , the other three areas are now discussed.

4.4.5.1 Timber sash and frame production

Window sash and frame are made of timber. Timber profiles are processed on various saw, milling and pressing machines. After the sashes and frames are prepared, they are vacuum impregnated to enhance their durability and service life. The average energy consumption for the production of one frame and sash is estimated to be 16.3 MJ and 16.9 MJ respectively, providing a total timber manufacturing energy of 33.2 MJ (Weir, 1998).

4.4.5.2 Sealed glass unit production

This involves the cutting of glass panes with precision, on a CNC glass cutting machine, washing, fixing the aluminium spacer, filling the infill gases and sealing the whole unit. An analysis has shown an annual energy consumption of 1367 GJ, that yields an energy content of 6 MJ for producing the sealed glass unit for one window.

4.4.5.3 Factory services

Factory services consume a significant amount of energy that is not directly related to windows production. However this energy consumption, categorised as overheads, has to be affiliated with the embodied energy of windows. This energy consumption , basically composed of lighting and heating of various departments in the factory, is estimated as 97.7 MJ per window produced. Table 4.6 presents the energy distribution of manufacturing processes involved.

4.4.6 Total embodied energy of an aluminium-clad timber window

Aluminium, glass and timber have been found to be the major energy expensive elements in a window. In terms of infill gases, Argon requires only a small amount of energy to be produced, Krypton consumes a considerable amount of energy, while Xenon requires a great deal of energy to be produced. Taking into account all these factors within the boundaries of this assessment, the embodied energy of a standard aluminium clad timber window has been quantified as 899 MJ, 1402 MJ, and 5.4 GJ respectively for Argon, Krypton and Xenon infill gases, as shown in Table 4.7. As discussed earlier in section 4.4.1.3, the extra energy associated with introducing aluminium cladding on a timber window is 161.6 MJ. Energy contents of similar windows without aluminium cladding are also given in Table 4.8. It is therefore, calculated that aluminium cladding brings an additional 21.8%, 13% and 3% of the embodied energy, respectively for Argon, Krypton and Xenon filled double glazed windows (Fig. 4.6). The detailed life cycle sketch of an aluminium clad timber window is shown in Fig. 4.7, which also explains production/extraction of raw materials and processing involved at various stages.

4.5 ENVIRONMENTAL ANALYSIS

Every material and process involved in window production contributes to environmental loads to some extent, however the scope of this study covers the following materials as the major loads inflicting entities.

4.5.1 Aluminium

The production of primary aluminium can be divided into four main stages: mining of raw bauxite, Bayer refining, primary smelting and metal finishing. All these four processes, due to materials and energy involved, are very important in the life cycle assessment of aluminium. The mining and crushing of raw bauxite is a high energy intensive process. Through the Bayer process Bauxite is refined to Alumina. The metallic aluminium is produced from the Alumina through the Hall-Heroult process commonly referred to as smelting. It requires large amounts of electricity and plants are often located near hydroelectric power stations. The last step is the casting of molten aluminium produced into the blocks or ingots. Chemical reactions that take place during production of aluminium from bauxite, are as follows.

$$Al_2O_3.xH_2O + 2NaOH \text{--->} 2NaAlO_2 + (x+1)H_2O \quad (4.1)$$

$$2NaAlO_2 + 4H_2O \text{--->} Al_2O_3.3H_2O + 2NaOH \quad (4.2)$$

$$2Al_2O_3 + 3C \text{--->} 4Al + 3CO_2 \quad (4.3)$$

The production process of secondary or recycled aluminium is fairly simple and requires less energy as compared to primary aluminium. In this process collected aluminium scrap is shredded. Steel fragments are removed by magnetic sorters. Paints and other impurities are removed by recirculating air. The aluminium fragments are then remelted and cast into ingots. Ingot from remelting can directly replace primary ingots from smelting plants. Depending on the intended use it is alloyed and rolled, forged, or extruded. These process steps are assumed to be identical for both primary and recycled aluminium. Figures 4.8(a) & 4.8(b), extracted from Habersatter (1991) as reported by Edwards (1996), show the basic processes involved in production of primary and recycled aluminium, also, highlighting the material inflow and waste generated in the processes.

Aluminium requires a great deal of energy to be produced, as discussed in section 4 4.1.1. This energy consumption in itself brings environmental burdens besides the large amounts of pollutants released during the production process. The pollutants resulting from aluminium production process have been highlighted by numerous researches, for example, Berge (2001) and IAI have indicated a number of polluting substances including, carbon dioxide (CO_2), acidic sulphur dioxide (SO_2), polyaromatic hydrocarbons (PAHs), and gases having global warming potential i.e., perfluorocarbons (PFCs), tetrafluoromethane (CF_4) and hexafluoroethane ($C F_6$). Part of these pollutants is washed off with water and then rinsed out into the sea or water courses without treatment, while gases escape the washing down with water and come out as air pollutants instead. Emissions into both air and water can have very negative consequences for the local environment and its human population. PAH substances, fluorine and aluminium ions remain in the sludge and slag from the production process. This causes problems in the ground water when deposits have to be stored on site.

Aluminium's capacity to be recycled easily has been one of its key advantage. In its first incarnation it is a comparatively expensive material, partly because of the large amounts of energy consumed in smelting the alumina into aluminium. Aluminium can be recycled repeatedly without any deterioration in quality. The more often the metal is recycled the more competitive its life time cost becomes.

4.5.2 Timber

Trees sustain life by absorbing water from roots and leaves and carbon-dioxide from the air. Interacting with sunlight through the process of photosynthesis they release the most vital gradient of life oxygen. In addition forests make life sustainable in many indirect ways; they not only help cool the land to enhance rainfall but also slow down wind evaporation. Forests help in preventing erosion of land to act as a barrage against flood and rainfall. Without forests the rain and snow melting during summer would result in droughts on one hand and floods on the other as the soil is stripped of nutrients.

Timber is the traditional construction material. Using timber as a construction material is environmentally sound. Forests are being protected well in most parts of the world through proper forest management schemes that is, for every tree that is cut, two trees are planted. It is also understood that younger trees have more tendency of carrying out photosynthesis process hence being more environmentally friendly. Therefore, the constant harvesting and replanting of trees is more beneficial in reducing carbon dioxide and increasing the supply of oxygen than simply leaving mature trees standing. The timber studied in this research is also environmentally controlled as a renewable resource through a well organised tree management programme in Scandinavian countries.

Timber is also considered to be a recyclable material since at the end of the service life of the product , it can be downcycled. It can be used for many purposes for example, in chipboard production, animal bedding or garden projects. Timber constituents of a window are disposed off in a number of ways such as land filling, incineration and down-cycling In the absence of any leg slative restrictions, there is not any particular disposal technique The disposal method adopted is rather an economical decision.

4.5.3 Glass

The materials used for glass production vary a lot depending on the properties required for specific applications of the glass product. Although there are slight differences in the amount and types of the additives used to make glass of different colours, the total amount of additives is very small as compared to the amount of major components. The fundamental glass making process and raw materials consumption is shown in Fig 4.9, extracted from Edwards et al (1999). Most of the major raw materials can be directly extracted from the earth by quarrying and need only minor treatm nt. About 26 of the sand used in glass production requires special treatment with hydrogen fluoride to produce chempure sand Sodium carbonate was traditionally produced from lime-stone and sodium hydroxide but due to environmental considerations most sodium carbonate is now produced directly by quarrying (Edwards et al 1999). Glass is a recyclable material. Rejected parts from the moulding process have always been melted for recycling whereas post-consumer recycling is also very common practice now.

The most important environmental factors associated with glass production are the hi h primary energy consumption with related energy pollution and the material pollution. Glass manufacture, which involves heating the batch to high temperatures, make use of oil, gas or electricity. All these fuels involve, at some point, the release of CO_2 and other gases. Pollution by quartz dust and calcium chloride can also occur. When tin oxide is applied as a vapour, hydrogen chloride and hydrogen fluoride are emitted, in addition to tin pollution. Glass does not produce pollution when in use, but both antimony trioxide and arsenic trioxide can seep out after disposal, causing environmental pollution. As a whole, glass has a Global Warming Potential of 569g/kg . Table 4.9 as extracted from Berge (2001), shows pollution generation tendency of the basic constituents of the aluminium clad timber window, i.e., aluminium, glass and timber.

4.5.4 Infill gases

Argon, Krypton and Xenon are present in atmosphere in small proportions as shown in Table 4.10. A detailed study carried out by Muneer, T (1995) shows the schematic diagram of the BOC gas production unit at Middlesborough (Fig. 4.10). Extraction of Krypton and Xenon are energy extensive processes. These gases reduce the thermal heat loss from the window, resulting into overall energy saving. It is reported that despite the high energy contents and affiliated environmental loads (Table 4.11) with double glazed windows using Ar, Kr and Xe, the amount of CO saved is 3.05 tonne, 3.7 tonne and 3.1 tonne respectively within 20 years of window's life.

4.5.5 Powder coating

There is waste produced during the pre-coating and powder coating process. To meet the environmental protection standards, the exhaust water in the tanks containing the waste particles is taken for cleaning into the treatment process before it leaves for exhaust. The sludge extracted from the water is dried up with the help of a press that further extracts out the moisture from it, that is later collected by a waste disposing agency. During the powder coating, 70 o of the powder is fused to the profiles, with the remaining being collected from the chamber for reuse. Reclaiming undeposited powder is accomplished by having the spray booth attached to a vacuum system having a cyclone and filters to collect the powder. This arrangement collects the large powder particles and traps the smaller "contamination" particles in a waste receptacle. The air is clean enough to be exhausted into atmo phere without further treatment. During the colour changing process a s gnificant amount of powder (18 o of the total) is wasted, that is returned to supplier. An attempt was made to obtain the data to calculate the environmental loads affiliated with powder coating process, but due to unavailability of necessary information, this was not possible.

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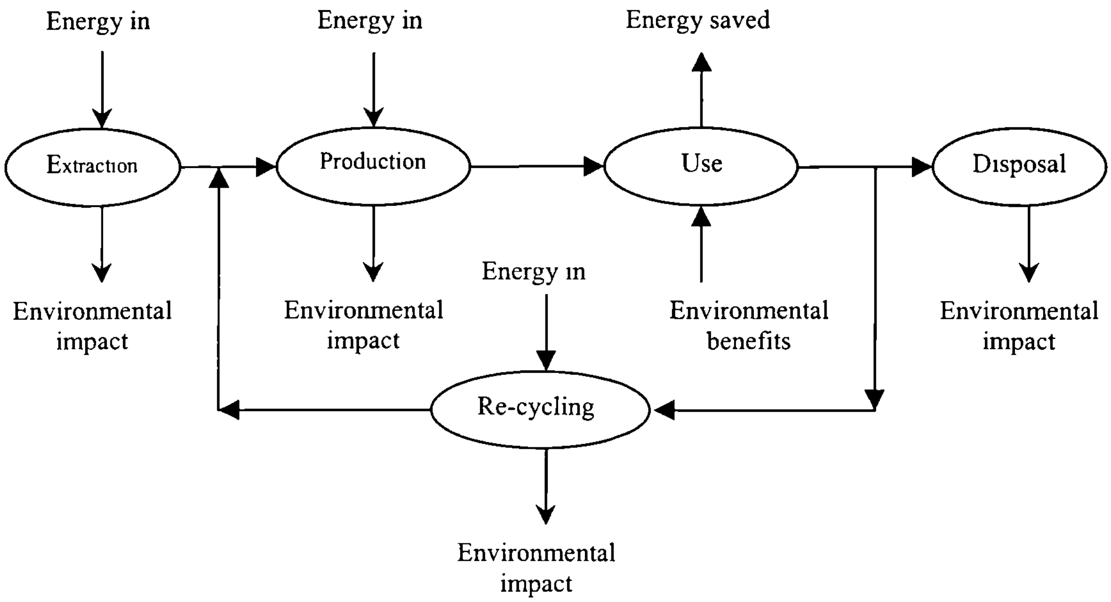

Fig. 4.1 Basic life cycle of a material highlighting the 'cradle to reincarnation' approach

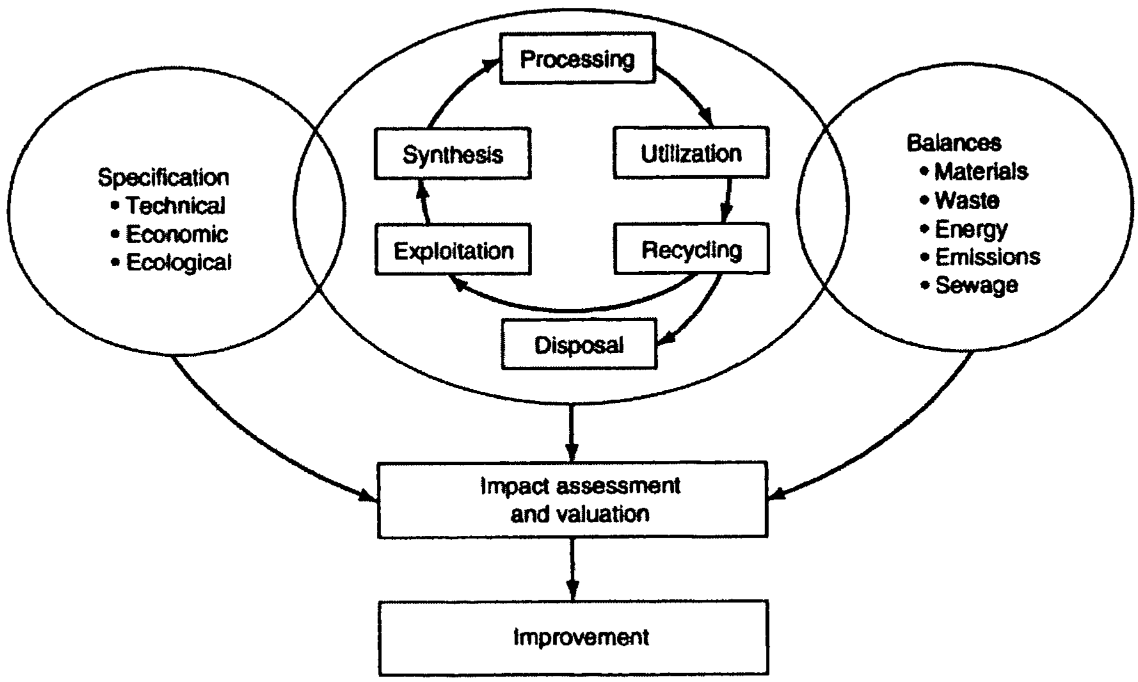

Fig. 4. 2 Factors considered in the life cycle assessment

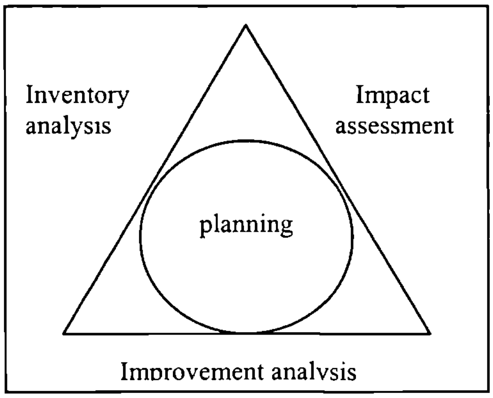

Fig. 4.3 Four main interactive steps for a complete life cycle assessment

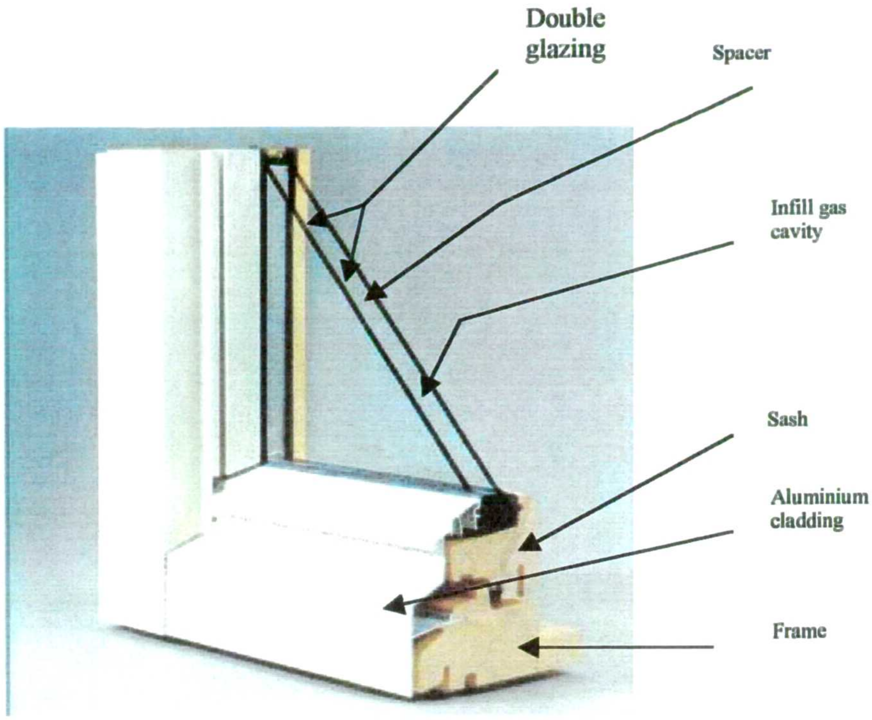

Fig. 4.4 (a) A cross section of an aluminium-clad timber window

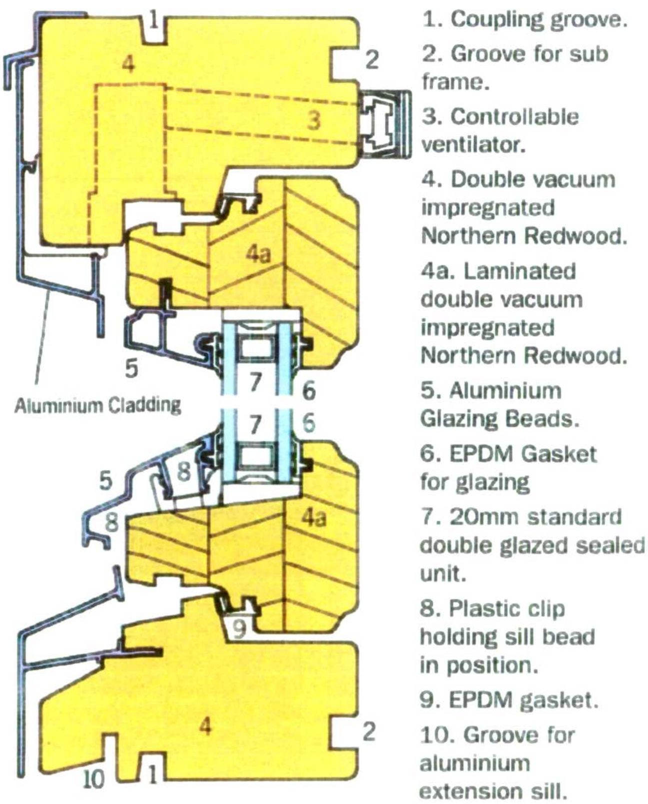

Fig. 4.4 (b) Side view of an aluminium-clad timber window

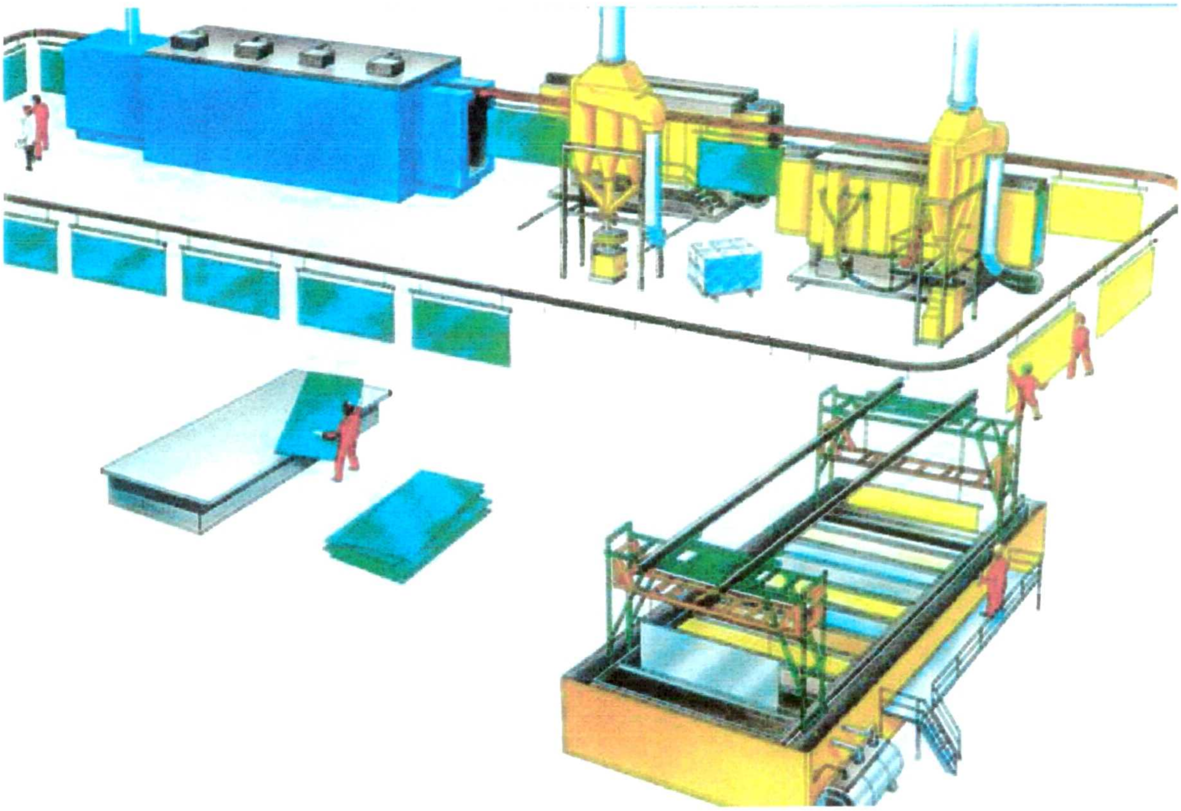

Fig. 4.5 Lay out of powder coating unit in Norway, showing all the processes involved

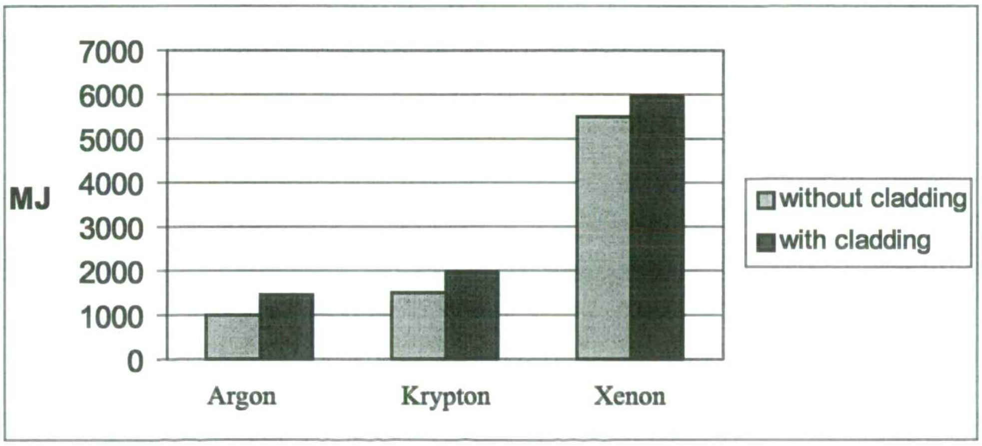

Fig. 4.6 Embodied energy of simple and aluminium clad windows for the three infill gases, Argon, Krypton and Xenon

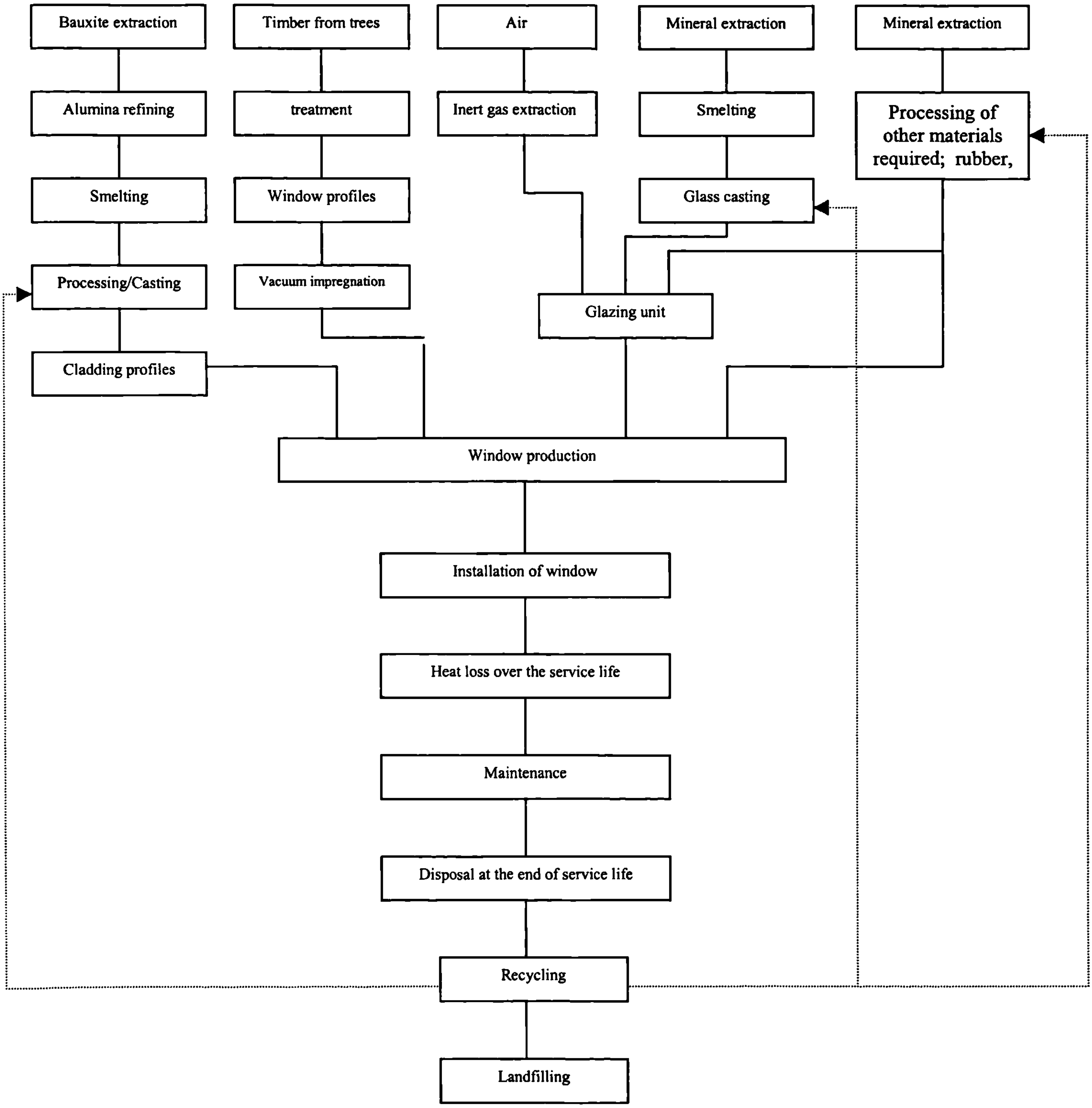

Fig. 4.7 LCA of an Aluminium-clad timber window (refer Tables 7 & 9)

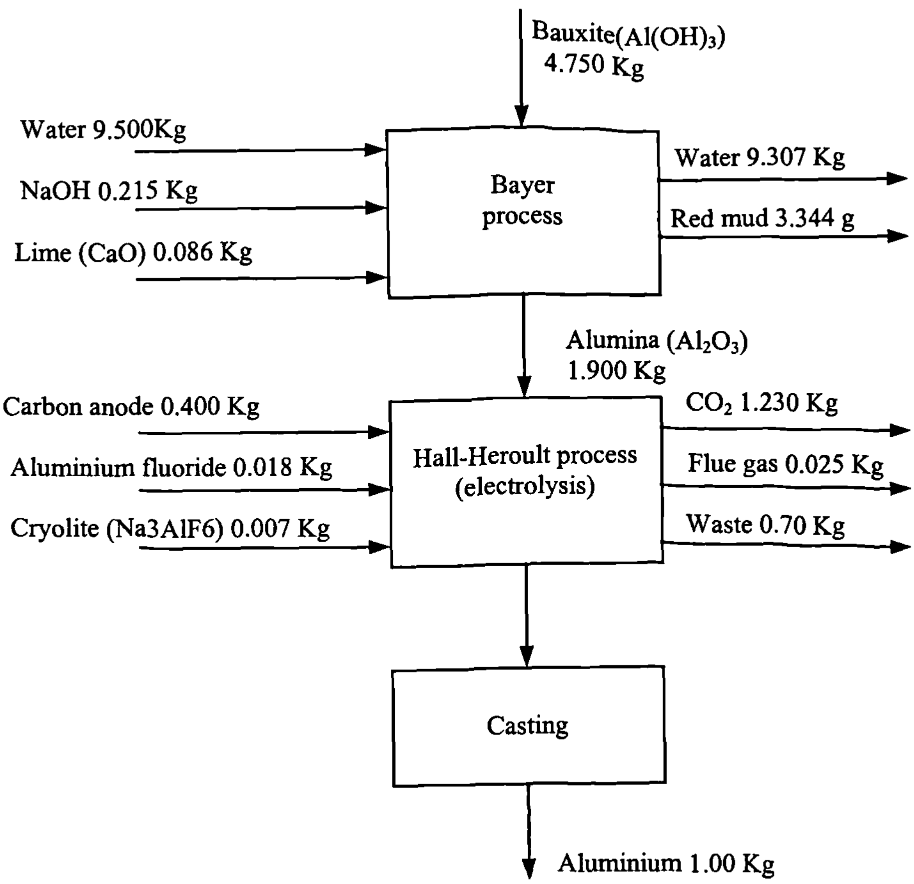

Fig. 4.8(a) Primary aluminium production from raw material

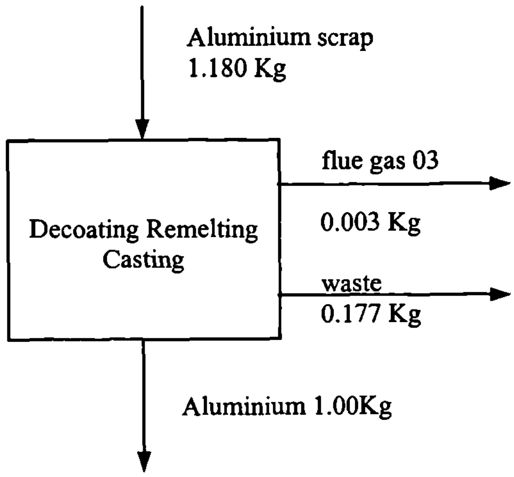

Fig. 4.8(b) Recycled aluminium production

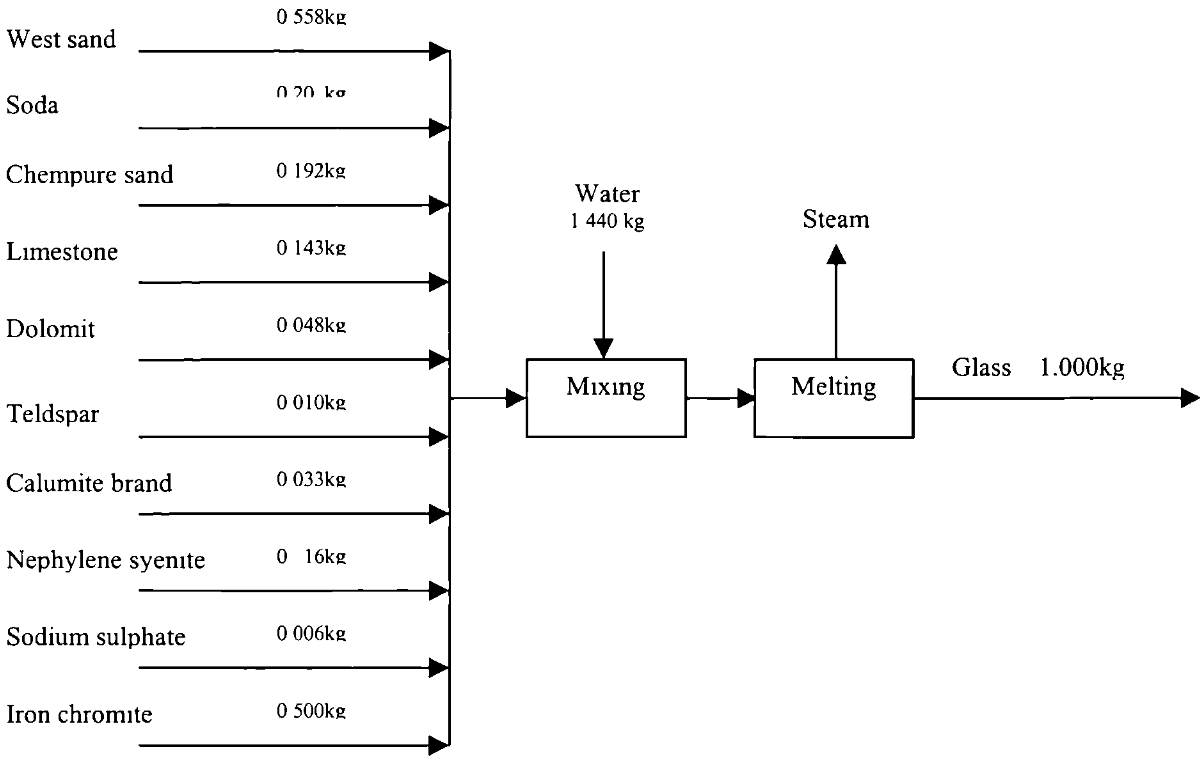

Fig 4 9 Production of glass

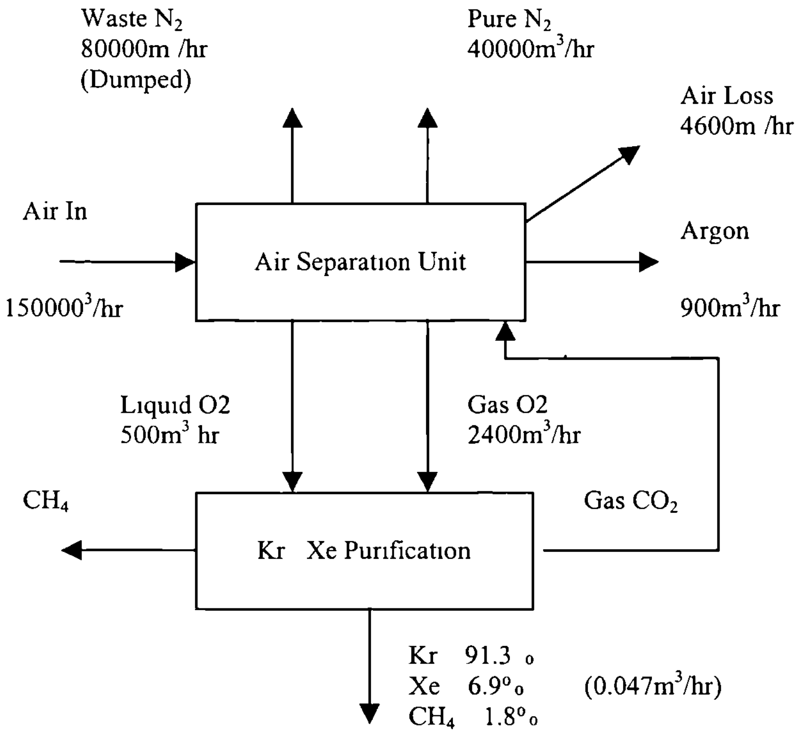

Fig. 4 10 Gas production schematic for BOC Middlesborough plant

Table 4.1 Physical properties of 6063 aluminium alloy

Density	2700 kg m^3
Modulus of elasticity	69 GPa
Coefficient of thermal expansion	23.5 x 10-6 C
Thermal conductivity	201 W (m.k)
Electrical conductivity	52°o IACS
Approximate melting range	615 C to 650 C

Table 4.2 Process involved in aluminium production and their respective energy consumption

Operation	Energy (MJ kg)
Mining and shipping bauxite	4.5
• Mining	(1.2)
• Shipping	(3.3)
Refining ore (Bayer process)	39.2
• Chemicals	(2.8)
• Extraction	(28.8)
• Calcination	(6.0)
• Shipping alumina	(1.6)
Smelting (Hall-Herout process)	162.1
• Electric power	(131.5)
• Energy value of coke	(22.9)
• Forming and baking anodes	(2.9)
• Cathode replacement	(2.6)
• Chemicals (electrolyte)	(0.3)
• Environmental control	(1.9)
Fabrication*	26.1
• Melting, holding and casting	(6.8)
• Preheating, forming and heat treating	(19 3)
Total	231.9

* Highly variable, depends on alloy and product

Table 4.3 Energy consumption for powder coating of 3.91 kg of aluminium profiles, to clad one window

Entity /Function	Energy (MJ)
Power consumed	26.92
Powder	0.135
Total	27

Table 4.4 Summary of energy contents of cladding a window with powder coated aluminium profiles

Entity Function	Energy (MJ)
Embodied energy of aluminium metal	214
Powder coating	27
Manufacturing cutting of profiles	2.36
Total	243.4

Table 4.5 Estimated aluminium mass used on the aluminium clad standard Nor Dan 1.2 m by 1.2 m window

Window component	Aluminium mass (Kg)	Waste %	Total aluminium mass (Kg)
Glazing unit spacer	0.241	3	0.248
Frame ventilation	0.159	17	0.186
Window mechanism	0.174	17	0.204
Total	0.574		0.638

Table 4.6 Energy contents for manufacturing processes

Function	Energy requirement per window (MJ)
Timber sash and frame	33.2
Sealed glass unit	6.0
Aluminium processing	2.362
Lighting and factory services	97.7
Total	139.3

Table 4.7 Summary of embodied energy of a standard aluminium-clad timber window

Window entity function	Embodied energy of Argon filled window (MJ)	Embodied energy of Krypton filled window (MJ)	Embodied energy of Xenon filled window (MJ)
Inert infill gas	0.01	502.8	4500.0
Timber	195.3	195.3	195.3
Aluminium profiles	214 0	214.0	214.0
Powder coating	27.0	27.0	27.0
Aluminium parts	34.75	34.75	34.75
Glass	289.4	289 4	289 4
Manufacture	139.3	139.3	139.3
Total	**899**	**1402**	**5400**

Table 4.8 Summary of embodied energy of a standard timber window

Window entity function	Embodied energy of Argon filled window (MJ)	Embodied energy of Krypton filled window (MJ)	Embodied energy of Xenon filled window (MJ)
Inert infill gas	0.01	502.8	4500.0
Timber	195.3	195.3	195.3
aluminium	114.0	114.0	114.0
Glass	289.4	289.4	289.4
Manufacture	139.3	139.3	139.3
Total	**738**	**1241**	**5238**

Table 4 9 Pollution contribution of basic window materials in Scandinavia and Europe

Material	Scandinavian peninsular			European continent		
	GWP	AP	POCP	GWP	AP	POCP
Aluminium	1900	13	3	11102	60	119
Glass	600	4	4	569	44	2
Timber	40	0.6	0.8	116	1	1

GWP Global Warming Potential in grams CO_2 equivalents
AP Acid Potential in grams SO_2 equivalents
POCP Photochemical Ozone Creation Potential in grams NO_x

Table 4.10 Composition of air

Gas	Percentage by volume
Nitrogen	78.084
Oxygen	20.9476
Argon	0.934
Carbon Dioxide	0.0314
Neon	0.001818
Methane	0.0002
Helium	0.000524
Krypton	0.000114
Hydrogen	0.00005
Xenon	0.0000087

Table 4.11. Energy and environmental details of infill gases production

Gas	Specific energy consumption kJ litre	Environmental loads (kg CO litre)
Argon	0.672	0.00015
Krypton	38500	8 32
Xenon	511400	110.5

CHAPTER 5: LIFE CYCLE COST ANALYSIS & VALUE ENEGINEERING

5.1 INTRODUCTION

Life cycle cost analysis (LCCA) provides a system by means of which the total cost of a project over a given period, accounting for capital costs, running costs, maintenance and repair costs, and any other costs likely to be incurred throughout the life of a project, is estimated. Value engineering (VE) is the methodology which represents how a system works and then stimulates ideas as to how it can be made to work better at the lowest possible cost. Productivity and cost effectiveness, the main objectives of LCCA and VE investigations, are equally important in sustainable development.

In the present work, LCCA of aluminium clad timber and unclad timber windows have been carried out with six different glazing compositions. Later on in the chapter, value engineering has been discussed. Due to the typical nature of planning and other implications, value engineering analysis of aluminium clad timber window is beyond the scope of this project. An introduction to VE methodology and recommendations for value engineering framework of windows, have however been provided.

5.2 LIFE CYCLE COST ANALYSIS

Life cycle costing techniques can be applied in any area of economic decision making. They are particularly relevant to the proper identification and evaluation of the costs of durable assets. As a result, they are of special relevance to the building industry. Whether complete buildings or individual building elements are considered, a decision is being made to acquire assets that are intended to last and to be used for a number of years. These assets will commit the owner or user not only the initial capital costs, but also to subsequent running costs, and periodic repair or replacement costs. Equally importantly, decisions made at the initial design stage will invariably affect future running costs and the economic use of the building. For example, there are different ways to heat a building and to illuminate it, each with different initial and running cost profiles. Figure 5 1, extracted from Al Hajj (1991), describes the principle of life cycle costing, highlighting major costs a building/building element comes a ross.

Kirk et al (1995) defines LCCA as;

"Life Cycle Costing is an economic as essment of an item area s stem or facility that considers all the s n ficant costs of owner hip over its economic life expre sed in terms of equivalent dollars"

The definition by the British Standard Glossary of Maintenance Management Terms in Technology is;

"The technique of considering the total cost of ownership of an item of material, taking into account all the costs of acquisition, personnel training, maintenance modification and disposal, for the purpose of making decisions on new or changed requirements and as a control mechanism in service, for existing and future items" (Deveci, 1999)

Flannagan et al (1989), describes the application of life cycle costing techniques as:

- An evaluation technique helping to choose between competing options, whether these relate to a complete building, system or a material
- A basis for predicting future running costs
- A management tool to ensure that the facility is being used effectively and that maximum value for money is being obtained
- A basis for budgeting for future expenditure
- A means of considering total cost rather than merely initial capital cost

Since LCCA relies on the projection into the future, the selection of the economic criteria and speculation of future changes is critical. These include the choice of methodology, discount rate, analysis period, maintenance schedule, frequency of component replacement criteria that vary from project to project as discussed by Woodward (1997), Ashworth (1996) and Kirk et al (1995).

5.2.1 Objectives of life cycle costing

Life cycle costing's ultimate aim is to provide value for money for the client and this is done by identifying the lowest net cost options. Significant objectives of life cycle costing are stated below as described by the Royal Institute of Chartered Surveyors (Woodward, 1997).

- Detailing the current operating costs of assets such as individual building elements
- Identifying those areas in which operating costs might be reduced
- Identifying the total cost commitment rather than concentrating on initial capital cost
- Facilitating an effective choice between alternative methods of achieving a stated objective

5.2.2 Time value of money

The relevant costs in any LCCA are a combination of capital cost and running costs. Since these costs are incurred at different times they can not be treated identically, 'money today' not being equivalent to 'money tomorrow'. A life cycle cost approach must have as a central feature, the presentation of current and future costs in equivalent terms. Flanagan et al (1989) has expressed the concept of time value of money as;

Any acceptable investment appraisal technique must exhibit two properties.

- It should take account of all cash flows associated with investment
- It must make proper allowance for the time value of money

5.2.3 Durability and life expectancy

The life expectancy or durability is an integral part of a life cycle cost assessment. Durability depends on the use of an appropriate product that is installed properly using proven design features, and is properly maintained on a regular schedule. By producing more durable products the use of raw materials is reduced by ensuring that materials of the same durability are used during the construction process, therefore not sacrificing better quality components in a building when there is decay elsewhere. If there are any materials of a lesser quality, then it is important that they are easily replaceable while the more durable materials can be dismantled for re-use or recycling in the case of demolition. As far as resources are concerned, there is a clear advantage in using robust materials and allowing buildings to last as long as possible.

ISO/FDIS 15686-1 (1999) as reported by Westberg, (2001), defines the 'service life' as,

'the period of time after installation during which a building or its parts meets or exceeds the performance requirements'

It should also be remembered that durability is not only a quantifiable technical property, but it also has an aesthetic and fashionable side to it. Berge (2001) speaks on similar lines and says that it is quite a challenge to design a product that can outlast the swing of fashion. Especially with technical equipment, it is also important to consider an optimal durability rather than a maximum durability. Changes to new products can often show a net economical gain in terms of energy-saving criteria. Ashworth (1996) states that the obsolescence that eventually occurs in both design and technology are perhaps the main reason why generally sound components are removed and replaced. In other situations components decay or damages are the causes. Several authors, such as Seeley (1996) and Ferry et al (1991) highlighted common scales which normally determine the life span of a product. Ferry, for example, lists following five determinants for a product's life expectancy.

Functional Life the period over which the need for the asset is anticipated;
Physical life the period over which the asset may be expected to last physically, to when replacement or major rehabilitation is physically required;
Technological life the period until technical obsolescence dictates replacement due to the development of a technologically superior alternative;
Economic life the period until economic obsolescence dictates replacement with a lower cost alternative;
Social and legal life the period until human desire or legal requirement dictates replacement.

5.2.4 LCCA and ecology

Construction and operation of a building is cost demanding and the environmental impacts caused, due to materials and energy involved, amongst other factors, are significant . Implication of LCCA is found when considering economics and ecology together, as also discussed by Sterner, E (2000) and Weidema (1998). United States Environmental Protection Agency highlights it as under;

In the environmental field, LCCA has come to mean all the costs with a product system throughout its life cycle, from materials acquisition to disposal. Where possible social costs are quantified; if this is not possible, they are addressed qualitatively (USEPA, 1995b).

Similarly with windows, economics and ecology of windows go side by side. There are many features of a window which closely inter-link their economical and environmental aspects, for example;

- Materials The materials constituting a window should be not only the economical but should also possess least possible burden on environment.
- Thermal performance Energy medium used Thermal performance of windows has economical as well as environmental significance.
- Maintenance choice of maintenance techniques are also important on both counts - economical and environmental aspects
- Disposal disposal of windows at the end of service life is environmentally more important than its economical aspect.

5.3 LCCA OF NOR-DAN WINDOWS

Life cycle cost analysis (LCCA) has been carried out for Nor-Dan aluminium-clad timber and timber windows. The LCCA covers the capital and maintenance costs of the windows. Life cycle cost analysis has been carried out for a life span of 40 years since the expected service life of aluminium clad windows is not less than 40 years while the quality timber windows also have the reputation to last more than 35 years. Component Life Manual by Housing Association Property Mutal (HAPM), has also provided similar estimations of service life as will be discussed in later sections. The costs included in the life cycle cost analysis are as under:

- Capital cost
- Energy (heat loss) cost; electricity or gas
- Planned maintenance cost; painting or staining
- Cleaning cost

Maintenance cost comprises of energy (heat loss) cost, window cleaning cost and painting or staining cost. Heating source in buildings can be either electricity or gas, therefore energy costs are provided both for electricity and gas based heating systems. Similarly both the painting and staining costs are provided. All costs have been calculated for a period of 40 years assuming an annual inflation rate of 3% (Langdon et al 1995), and using Single Compound Amount Formula (SCA) that provides the future sum of money in terms of present value, as described under.

$$F = P * (1+i)^N \tag{5.1}$$

Where

P a present sum of money

F a future sum of money

i an inflation rate

N number of inflation years

Energy cost greatly depends upon the local climate and temperature conditions that vary from location to location. This analysis, therefore, has been carried out for five different locations within UK. These are: Aberdeen, Edinburgh, Manchester, Wales (southern part) and London.

5.3.1 Capital cost

Capital cost is the initial investment to buy and get the window installed. Capital cost for aluminium clad timber and timber windows as provided in cost analysis values (Tables 1-5), varies not only with the type of frame but also with the glazing composition.

5.3.2 Energy (heat loss) cost

Windows can be a major source of energy loss or gain in buildings, especially in harsher climates. Windows have a direct impact on the energy efficiency of any given building. The improved characteristics of windows can lead to substantial energy savings as a result of their use. Energy is transmitted through a window via radiation, conduction, convection and air leakage. Energy cost in the form of heat loss through the window is a major part of the life cycle cost of the window. Energy cost becomes particularly significant in colder weather conditions. For example, for the double glazed air filled window as shown in Table 6, annual heat loss in London is 202.4 kWh while in Aberdeen it is 274.9 kWh. The energy cost makes up a considerable proportion of the whole life cost as it accounts for 43% and 50% for the two mentioned cases, respectively. Figure 5.2 shows the heat loss for six different glazing compositions at an Edinburgh location.

5.3.2.1 *U value*

U value of a window is defined as the rate of heat lo s per square metre, under steady state conditions, for a temperature difference of one Kelvin betwe n the inner and outer environments separated by the glaz ng system. It is expressed in W m K.

The total heat lost is proportional to the U-value of a given window. The lower the U-value the higher the thermal resistance and lesser the heat loss. U value depends upon a number of factors such as geometric structure of window and glazing unit, glazing unit composition, i.e., glass type, infill gases and low emissivity coatings. Figures 5.3 & 5.4, extracted from Muneer et al (2000) show the heat loss mechanism and thermal circuit of a double glazed window, respectively.

5 3 2.2 *U value and Infill gases*

The U-value can be significantly reduced by using inert gases within the glazing cavity. Argon, Krypton are the inert gases normally used while Xenon is less common because it in itself requires a large amount of energy to be produced as discussed in section 4.4.2.2.

5.3.2.3 *U-value and glazing layers*

U-value can also be reduced by using multiple glazing units. Significant savings in energy cost can be obtained by using double or triple glazed windows. Values provided herein (Tables 5.1-5.6) indicate that U-value of a triple glazed window is 20% lower than the double glazed window of the same type.

5.3.2.4 *U value and low e coatings*

Low-emittance (low-e) coatings are microscopically thin, virtually invisible, metal or metallic oxide layers deposited on a window primarily to reduce the U-value by suppressing infra-radiative heat flow. The principal mechanism of heat transfer in multilayer glazing is thermal radiation from a warm pane of glass to a cooler pane. Coating a glass surface with a low emittance material blocks a significant amount of this radiant heat transfer, thus lowering the total heat flow through the window. Figures indicate that energy cost can be reduced by an amount of almost 60 % by using low emissivity coated triple glazed unit with Argon infill gas. As shown in Table 6, at an Aberdeen location, for a double glazed air filled window the annual heat loss is 274.9 kWh while for a triple glazed Argon filled window with low emissivity coatings this heat loss is reduced to 112 kWh.

5.3.2.5 *Energy cost and the h ating m diums*

Gas fuel is much cheaper option than electricity and it can make significant saving in energy cost if gas is used as the heating source. Analysis shows that for simple double glazed windows in cold locations like Aberdeen LCC of windows can be reduced by 36 % just by using gas as the heating source instead of electricity Here it must also be known that the cost of electricity and gas supply varies across UK, depending upon many factors such as the number of consumers, local electricity networks and competition amongst suppliers. In order to establish the reference cost analysis, energy cost is calculated at moderate rates, i.e, 5 5 p/kWh electricity and 1 6 p/kWh for gas. Figure 5.5 shows the life cycle energy cost of a double glazed air filled window at various locations both for electricity and gas usage.

U-value of aluminium-clad timber windows is almost same as that of simple timber windows. Cladding therefore, does not make any difference towards running energy cost of windows.

5.3.3 Maintenance cost

In this analysis maintenance cost of windows consists of the scheduled painting and staining costs of frame. Other costs such as break down of handling or locking system, any problems with ventilation or sealing system or breakage of glazing, are not taken into account since these are assumed not to be routine costs. Such wear and tear costs also depend upon the maintenance and after-sale care of windows.

Timber windows are required to be painted/stained regularly in order to maintain their appearance as well as to provide resistance against weathering degradation. Timber windows are recommended to be painted externally on a 5 year cycle and stained after every 3 years. Internally, windows are painted normally after a life cycle of 10 years or more frequently depending upon the personal preferences, and staining can be carried out every 5 years. The total cost of internal paint on a 10 year cycle, over a 40-year life of window is calculated as £13.95. The total cost of internal stain of a window based on 5 year cycle, is calculated as £33.00. Similarly costs of external paint or stain based on 5 and 3 year cycles are calculated as £75.93 and £146.85 respectively. Therefore over the 40-year life, painting cost of a timber window is calculated as £89.88, and it will cost £179.85 if window is stained (Table 7).

Aluminium clad timber windows are painted or stained internally only, as they do not require any external maintenance. The powder coating paint on the aluminium cladding is expected to be stable enough to last over the studied period, hence externally it requires no painting maintenance. Timber underneath the cladding does not require any surface treatment either. Internal painting or staining cost of window is the same for a timber window. Therefore the total painting cost of aluminium-clad timber window is £13.95 over the 40 year life and £33.30 if it is stained.

5.3.4 Cleaning cost

Cleaning cost is the most significant cost over the life cycle of windows. Yearly cost of cleaning a window is estimated as £6 each for internal and external cleaning that gives a total amount of £12 per year. It gives the total cleaning cost over 40 year life of £892.91. Table 8 summarises annual cleaning cost information.

In domestic applications, windows are normally cleaned by the inhabitants themselves rather hiring professional cleaners. Elimination of cleaning factor in domestic sector can, therefore, enormously cut down the life cycle cost of windows. Figs 5.6(a) and 5.6 b) show the pie chart breakdown of life cycle cost of aluminium clad timber and timber windows with various maintenance combinations at an Edinburgh location. Again Figs 5.6 (c) and 5 6 (d) show life cycle cost breakdown of windows at an Edinburgh location, indicating that cleaning cost accounts for more than 60% and 40% of whole life cost of a window with gas and electricity heating systems respectively.

5.3.5 Cost analysis of aluminium-cladding

In terms of capital cost aluminium-clad windows are approximately 14-18% more expensive than timber windows. The running cost of aluminium-clad windows is less than timber windows. This is due to the fact that maintenance cost of an aluminium-clad windows is less than a timber window since the former does not require to be painted or stained externally like the latter one. Comparing the costs of aluminium clad timber and timber windows, this lower running cost of aluminium clad windows justifies their higher capital cost. Calculating the total cost over 40-year life, aluminium clad windows become a cheaper option than timber windows. For example, a double glazed low-e coated air filled aluminium clad timber window's capital cost is higher than the timber make, £ 183 and £154 respectively, that gives a difference of £29. Over 40 years, a timber window costs £119 and £48 more than an aluminium clad window with staining and painting maintenance respectively as shown in Fig 5.7. Figures 5. 8 (a) & 5.8 (b), show the comparative details of capital, running and total costs of aluminium clad timber and timber windows for domestic applications with gas-paint and gas-stain options, respectively. The figures show that in capital cost terms aluminium clad timber windows are more expensive than the timber design. In running cost aluminium clad timber windows are significantly cheaper than timber ones, and the aggregate of the two costs, i.e. total cost, shows that aluminium clad timber windows become the cheaper option. Similarly Figs 5.9 (a) & 5.9 (b) show the comparative costs of windows for commercial applications with gas paint and gas stain options.

5.4 VALUE ENGINEERING

5.4.1 Introduction to value engineering

Value Engineering is a system of analysis to ensure that facilities and equipment are designed, constructed, serviced and commissioned such that they may be used and maintained over a lifetime of use at the lowest possible cost of ownership.

The Society of American Value Engin ering defines value engineering as:

The systematic application of recognised techniques wh ch identify the function of a product or service, establi h a monetary value for that function, and provide the necessary function reliability at the lowest overall cost (Elias, 1998)

The key to Value Engineering is holistic design; the selection of each building component has knock on-effects for running and maintenance costs throughout the life of a building. Value engineering is not about short-term cost-cutting, rather it is about providing the most cost effective long-term project solution.

5.4.2 The value engineering approach

When applying VE, there are two key elements necessary in the search for value.

- Task team
- Methodology of the search

5.4.2.1 *Task team*

Value engineering studies rely on the services provided by a group of individuals. This group is called 'task team' and is made up of people representing those disciplines necessary to fully define the problem and its function and to arrive at a cost effective solution representing the best value. A team with the proper balance of commitment, competence, and stimulation is the most critical factor for a successful value analysis.

5.4.2.2 *Methodology of the search*

In value engineering, 'function' is most vital aspect. Function is the purpose or objective of the product or operation under consideration on those explicit performance characteristics that must be possessed by the hardware if it is to work or sell. A user purchases an item (or service) because it will provide certain functions at a cost the user is willing to pay. If the item does not do what it is intended for, then it is of no use to the buyer no matter how low the cost may be. Similarly spending more money to increase the function of an item beyond that which is needed does not increase the value to the prospective buyer. Since insuff cient functionality is unacceptable and too much functionality is wasteful, function must be carefully defined. This is the only way associated costs may be determined and properly assigned. Figure 5.10 describes the different combinations of functionality and cost, highlighting the most appropriate approach.

The initial efforts in VE study must therefore be directed towards determining the user's actual needs, i e the performance qualities or characteristics that must be maintained if the item is to be useful By defining the function, one learns which characteristics of the design are really required. The proper identification of function is, thus, very important to the successful implementation of value engineering.

5.4.3 Value

The term value is used in many ways and has several meanings. The value of a given item may differ according to whether it is viewed from the standpoint of the seller, the buyer or the user. Rousseau (web article) has described the value of windows in different ways. For example, for the occupant, windows bring natural light and solar heat, fresh air and a view to the outside world. For the architect and designer, windows shape the facade, interrupt wall or roof systems and require special detailing at their interface. For the engineer, they are sources of overheating, cooling or air infiltration. For the builder, windows are locations where many dissimilar materials and trades have to join together. For the fire engineer, windows can be an exit in case of fire, a potential path for flame propagation to other storeys or buildings, and a source of air to the fire. For the consultant, they may well be a source of revenue because windows can be associated directly or indirectly with performance failures.

Elias, (1998) classifies value in following seven types;

- Economic
- Moral
- Aesthetic
- Social
- Political
- Religious
- Judicial

Value engineering, however, is concerned only with economic value which is defined as;

The lowest cost to reliably provide the required function or service at the desired time and place and with the essential quality (Elias, 1998).

5.4.4 When to apply value engineering

The scope of value engineering effort depends on the size and complexity of the project. However, the highest return can be expected when VE is performed in the early stages of the project life cycle, when implementation costs are lower. This is the time before major decisions have been incorporated into the design and when VE recommendations have the greatest impact on costs. The same principle is applicable on LCCA. Figure 5.11, for example, has been referred by Flanagan et al (1983) to describe the effectiveness of LCCA with respect to time of implementation in any project. The same Fig. has also been referred by Elias (1998) to highlight the significance of VE at early stages of a project, he further describes five major stages of development for any project that are;

- *The concept formulation performance specification stage*

The purpose of the concept formulation stage is to translate general requirements into performance specification. VE effort in this phase is directed towards furnishing inputs that will achieve the functions sought, at the lowest possible cost. Improvements generated during this phase produce benefits lasting throughout the life of the project.

- *The preliminary design stage*

During the preliminary phase approved concepts are defined, and design specifications are started. Sufficient detailed information is developed to substantiate all quantities and costs that have been presented in the program directive. This is a good time to question performance characteristics and revise them if necessary. A VE study that analyses requirements, technical characteristics, and the design tasks may reveal possible alternatives, offering improved value.

- *final design stage*

It is during final design phase that design specification details are formulated and schedules created. VE efforts in this phase are limited to eliminating unnecessarily restrictive details. Usually redesign (as a result of VE) at this stage can not be economically accomplished, unless the life cycle savings potential is large enough to justify the expense.

- *The construction stage*

During the construction stage VE is accomplished by reviewing specific contract requirements and initiating change orders. Since change orders tend to increase contract cost, they should be subjected to value analysis to prevent adding non-essential functions and to facilitate finding other solutions that would lower the cost.

- *The operation and maintenance stage*

The total cost of ownership is affected by operation and maintenance costs. Reducing these costs result in lower life cycle cost. VE studies during this phase offer an opportunity to make changes that (perhaps due to lack of time or other constraints) were not made earlier.

5.5 VALUE ENGINEERING OF ALUMINIUM CLAD TIMBER WINDOWS

As discussed above, the best time to apply value engineering is at the planning and design stage. Aluminium clad window is an established product in market for many years now. A thorough value engineering of aluminium clad windows is beyond the boundaries of this study. This work therefore, does not addre s the holistic value engineering of windows, rather it provides the guidelines that could be adopted to analy e the existing product on the basic value engineering parameters.

5.5.1 Function of a window

Functionally, a window can be defined as a 'transparent wall'. Basically a window is composed of two parts, frame and glazing unit.

5.5.1.1 *Frame*

window frames are available in a wide range of framing materials such as

- Aluminium
- Aluminium with thermal break
- Timber
- Clad timber (aluminium or PVC clad)
- PVC
- Hybrid and composite
- Insulated PVC
- Fibreglass

5.5.1.2 *Glazing unit*

Glazing units are available in numerous compositions depending upon following elements involved;

- number of glass panes (glazing layers)
- infill gases
- low emissivity coatings
- type of glass

5.5.2 Window performance parameters

Frame and glazing combination, that make-up a window, is required to possess following characteristics;

- control heat flow
- control air flow
- control condensation
- control water vapour flow, rain and snow penetration

- control solar and other radiation
- control sound transmission
- provide strength and rigidity
- durable and economical to be maintained
- maintain satisfactory performance over service life
- be appealing and harmonious with the surroundings
- be environmentally sustainable

Value engineering analysis of a window, therefore, aims to achieve above stated functionality at the lowest possible cost over the entire life of the window. Different windows, depending upon frame and glazing composition, meet different levels of performance. Service life cost of a window is driven by its type; the nature of materials and technology involved both in frame and glazing unit, determine not only the capital cost but also running cost that depends upon maintenance requirements, U-value, and durability.

The most important characteristics for a window, thermal insulation (U-value), durability and maintenance are discussed below from a value engineering view point.

5.5.3 Thermal Insulation/ U-value

This is one of the most important function of a window particularly in harsh conditions. Heat flow or U-value is the property that depends upon the entire window configuration, i.e. window design, frame material, glazing unit's composition. There are a number of features that could be adopted to achieve better thermal insulation. For example, glazing layers, infill gases, low-e coatings can contribute towards significant reduction in overall U-value of the window. An excellent example is as demonstrated in Figs. 5.12 (a) and 5.12 (b). Figure 5.12(a) presents the infrared picture showing qualitative thermal performance of an air-filled, float-glass double glazed window having U-value of 3 W m^2-K. The significantly higher heat loss from the window is quite noticeable as it shows a red hot colour for the external window pane. The window was then replaced by a high insulation Ar-filled, triple glazing window having a U-value of 0.85 W m^2-K. As a result, the lower heat loss is quite evident (green-coloured rectangular shapes).

These features applied to achieve better thermal performance can significantly cut down the energy cost of a window reducing the running cost over the life time. This can be an economical choice when considering the life cycle cost of a window. It however, can result in increased capital cost. One therefore, has to evaluate the overall scenario considering both the increased capital cost and reduced running cost. This evaluation can help choose the best possible option over the service life of a window.

5.5.4 Durability and maintenance

This is a very important feature, desired in any window. Windows should not only be durable and stable enough to last over desired length of period (life span) but should also be economical in terms of their routine maintenance. Type and quality of materials adopted are amongst the vital fa tors that determine durability and routine maintenance.

Compared with glazing unit, frame materials are more sensitive towards natural weathering conditions which cause degradation resulting into increased maintenance requirements and reduced service life in the long run. In frames, these characteristics, resistance against environmental conditions and over all lower maintenance requirement, vary significantly from material to material. As shown in section 5.3 5, durable and better quality product turns out to be more economical in the life cycle costing despite their higher capital cost. A careful approach therefore, is required to be adopted in the selection of materials. Another factor to be considered is the repair aspect, e.g. window frames should be easy to repair in case of routine or accidental breakdowns.

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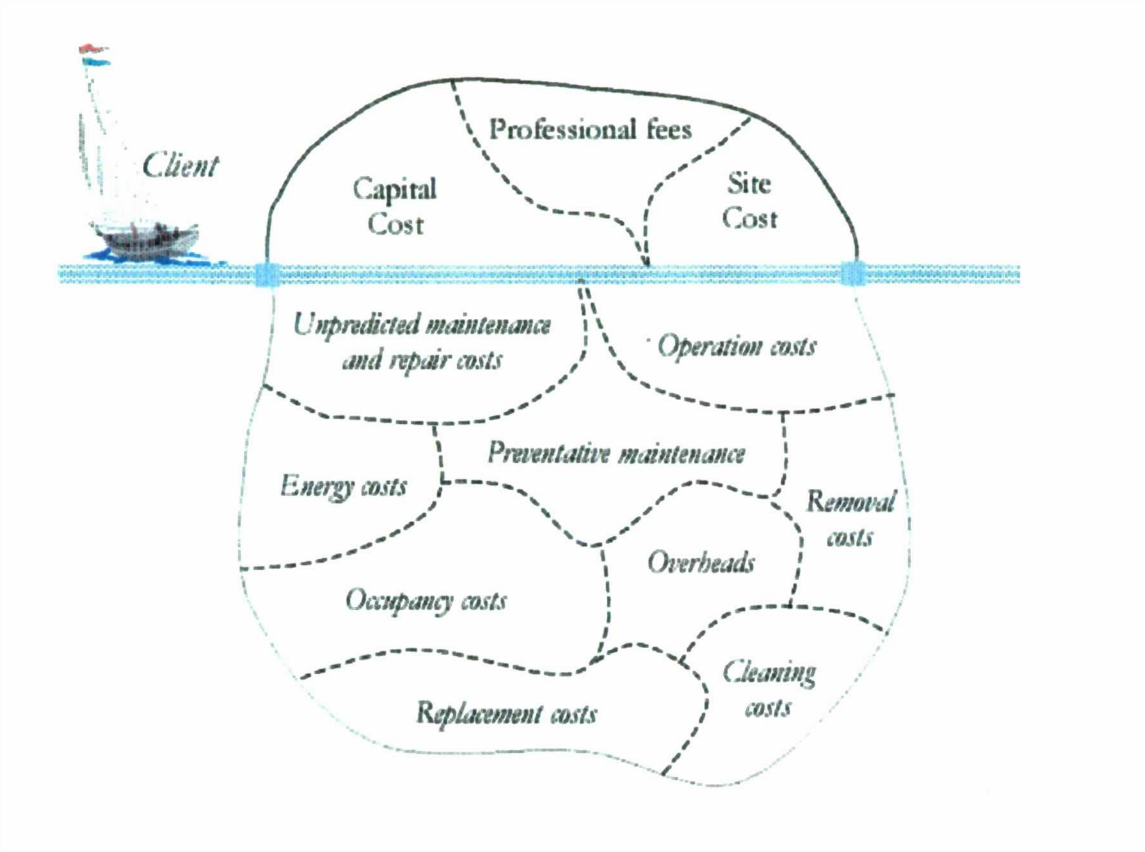

Fig. 5.1 Total life cycle cost of a building/building element

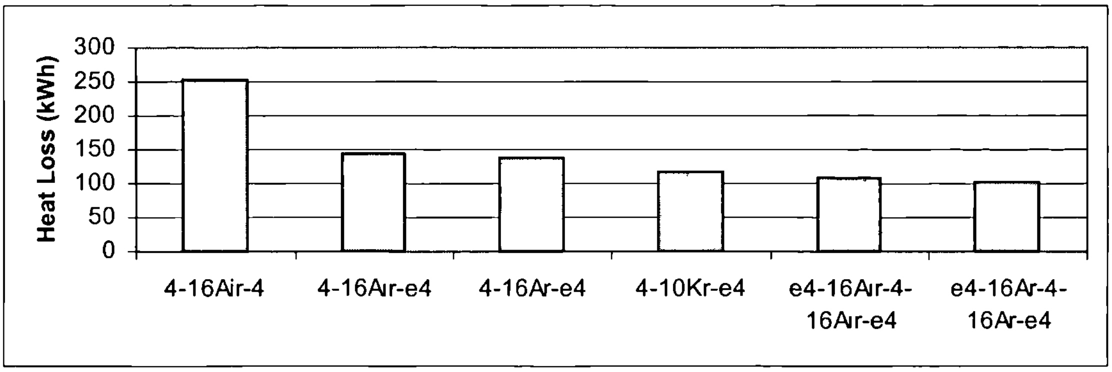

Fig. 5.2 Annual heat loss of different glazing compositions

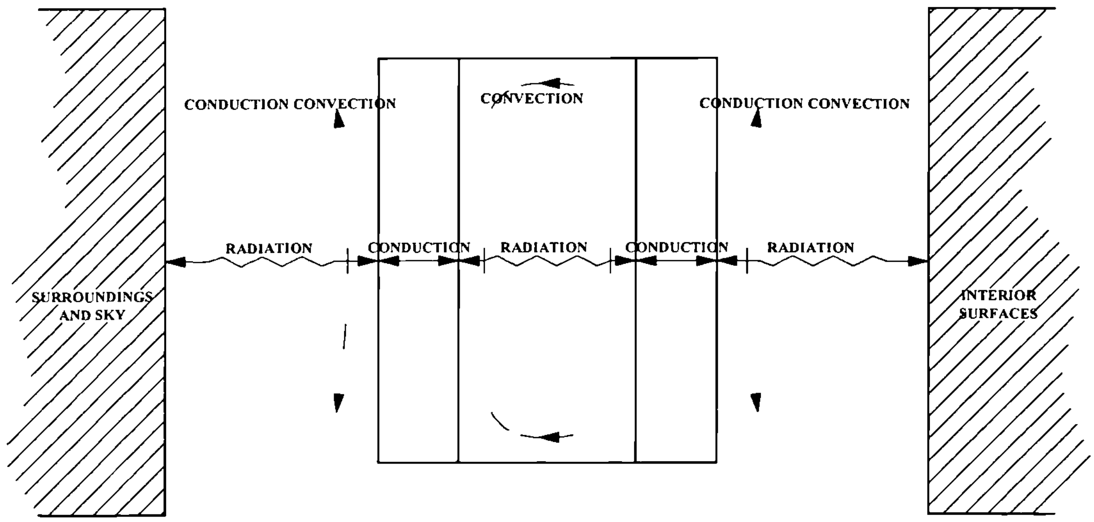

Fig. 5.3 Mechanism for heat loss through double-glazed units

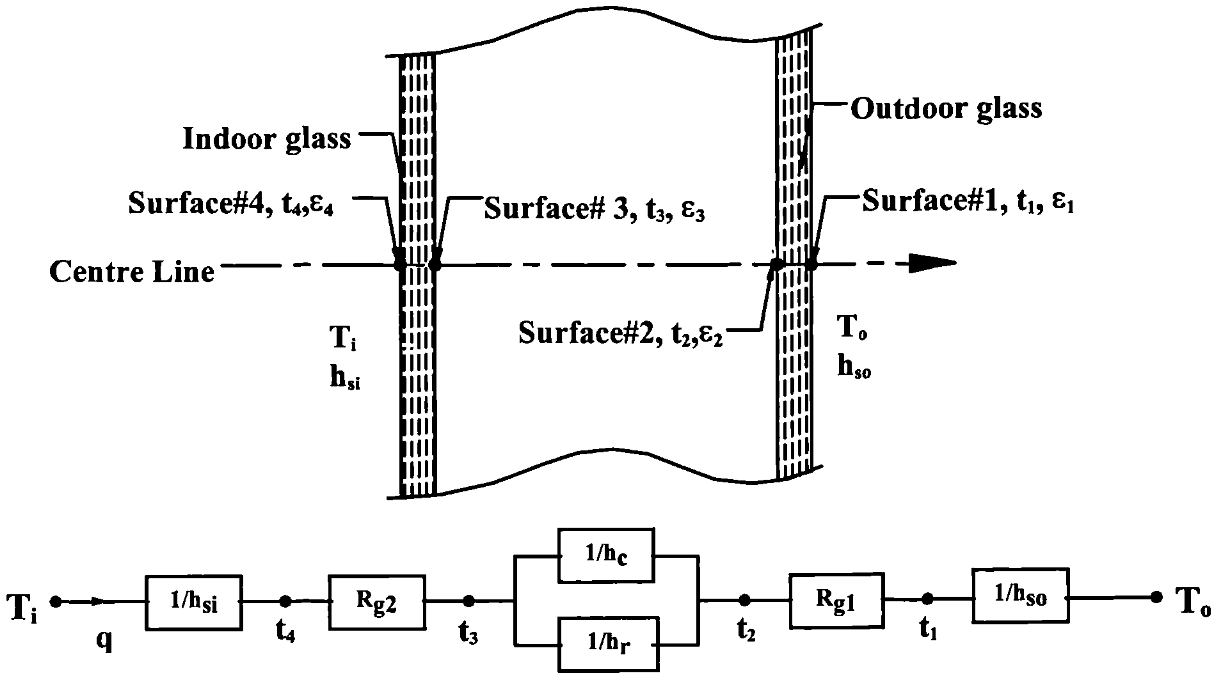

Fig. 5.4 Centre line thermal circuit for double glazed window

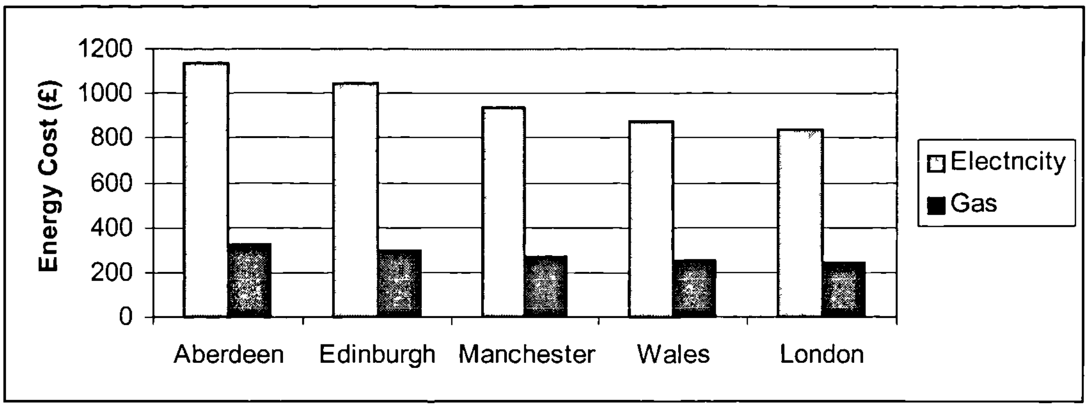

Fig. 5.5 Energy (heat loss) cost over the 40-year life of a double glazed air filled window

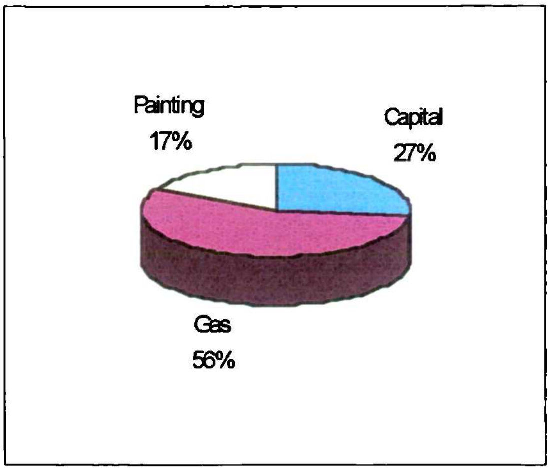

Fig. 5.6 (a) Timber window with paint-gas maintenance for domestic application

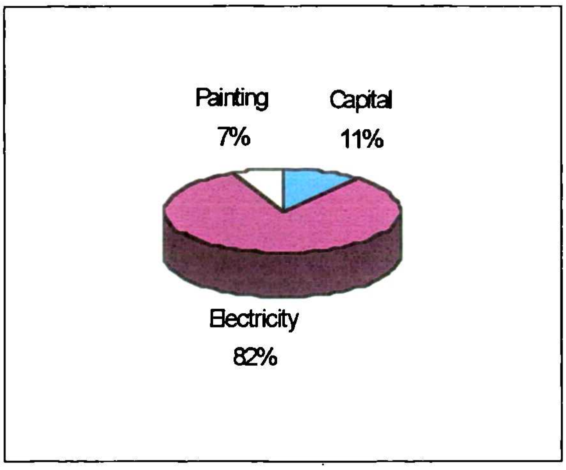

Fig. 5.6(b) Aluminium clad timber window with Paint-electricity maintenance for domestic application

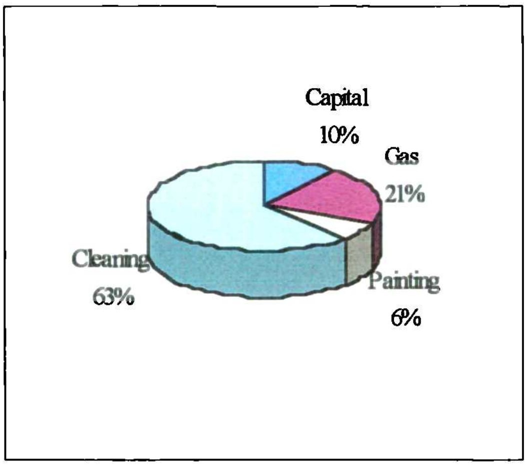

Fig. 5.6(c) Timber window with paint-gas maintenance for commercial application

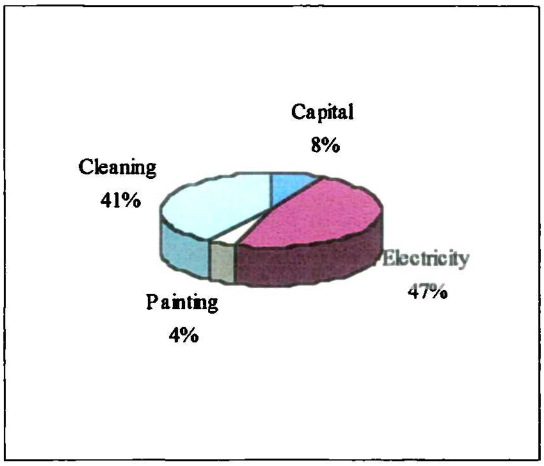

Fig. 5.6(d) Aluminium clad timber window with paint-electricity maintenance for commercial application

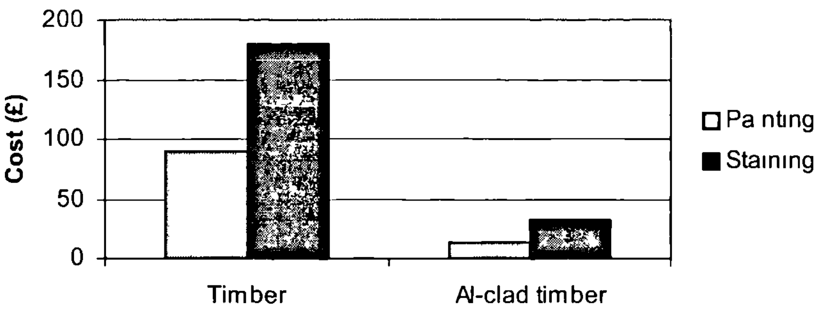

Fig. 5.7 Life time maintenance (painting staining) cost comparison

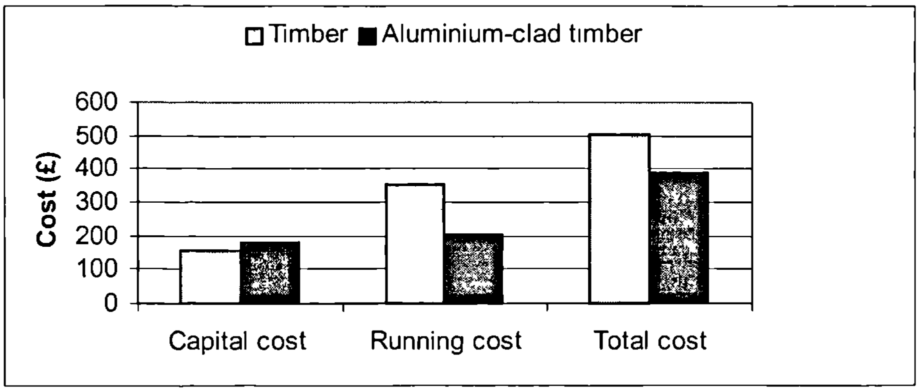

Fig. 5.8 (a) LCC comparison of low-e, air filled unclad timer and al clad timber windows Gas & staining maintained domestic application- Edinburgh

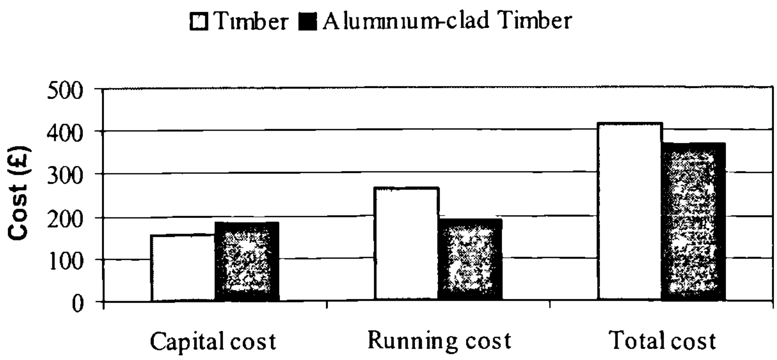

Fig. 5.8 (b) LCC comparison of low-e, air filled unclad timer and al clad timber windows Gas & painting maintained domestic applications Edinburgh

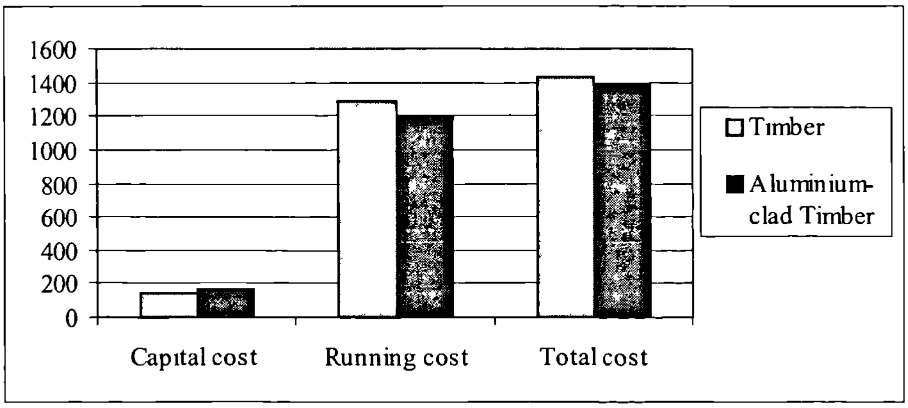

Fig. 5.9(a) LCC comparison of air filled unclad timer and al-clad timber windows
Gas & painting maintained commercial application –Edinburgh location

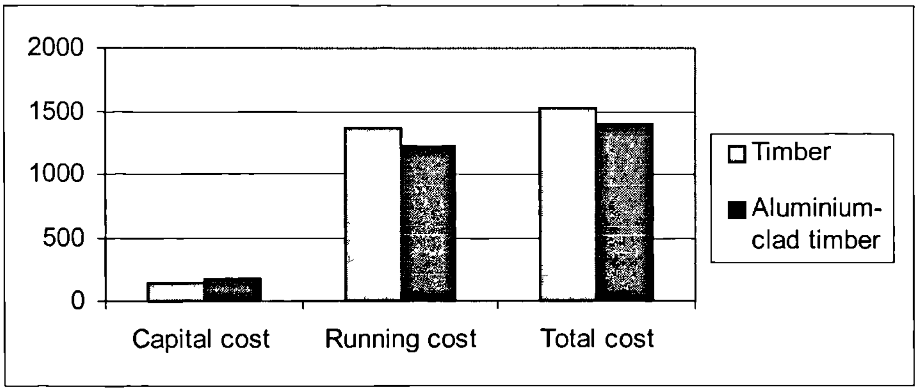

Fig. 5.9(b) LCC comparison of air filled unclad timer and al-clad timber windows
Gas & staining maintained commercial application Edinburgh location

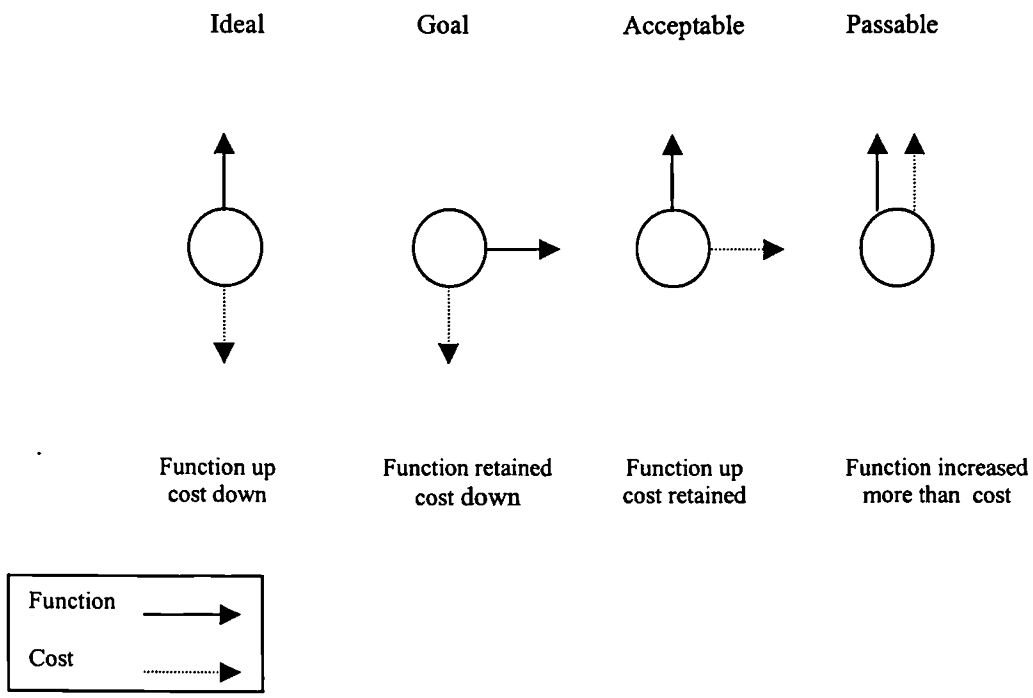

Fig. 5.10 Various ways of improving functionality

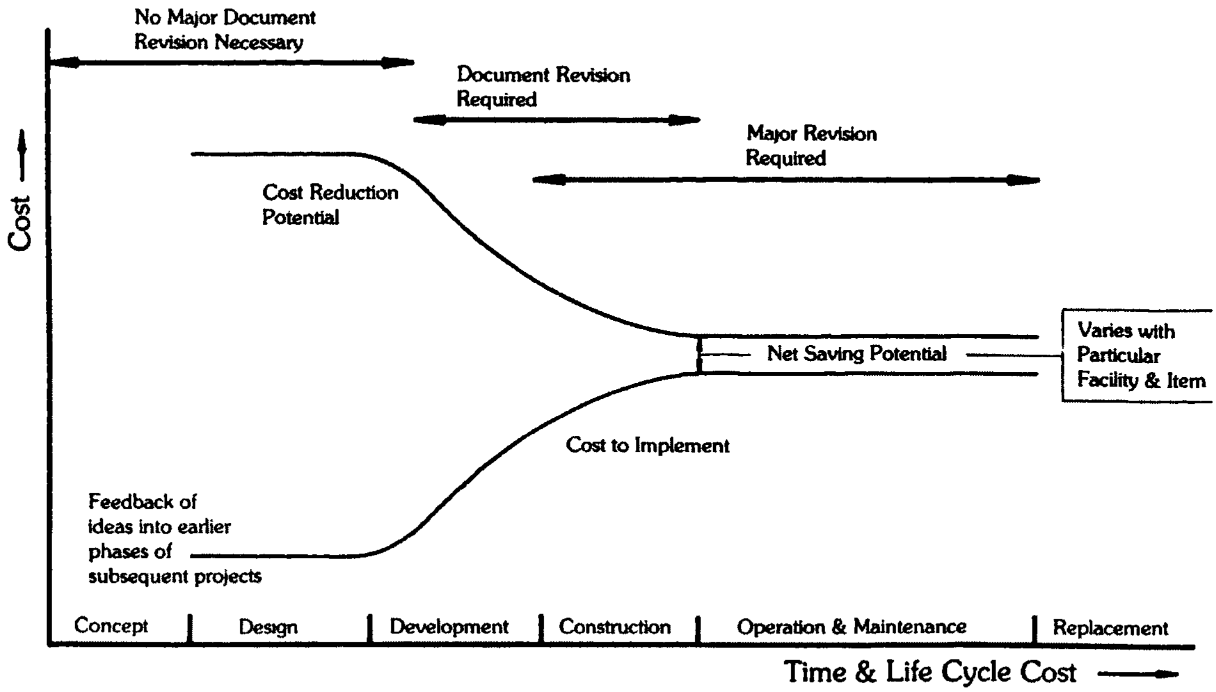

Fig. 5.11 Relationship between life cycle cost savings and timing of implementation

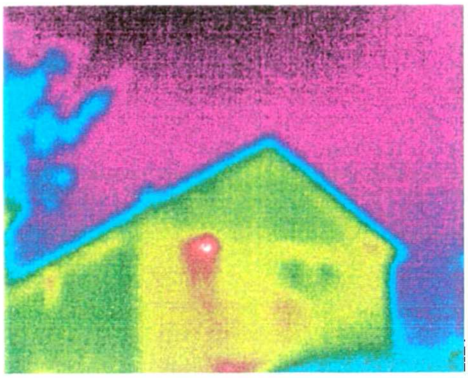

Fig. 5.12 (a) Red hot air-filled, float-glass double glazed window shows higher level of heat loss (Original is in colour)

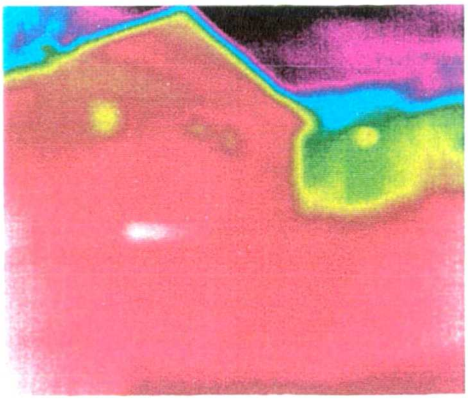

Fig. 5.12 (b) The green spot shows lower heat loss through the replaced Ar-filled triple-glazing window (Original is in colour)

Table 5.1 Life cycle costing of aluminium clad timber and timber windows at an Aberdeen location with 6 different glazing compositions with four different running options gas paint, gas stain, electricity paint and electricity stain - Commercial applications

Timber windows						Aberdeen
	4-16Air-4	4-16Air-e4	4-16Ar-e4	4-10Kr-e4	e4-16Air-4-16Air-e4	e4-16Ar-4-16Ar-e4
U-Value ($W m^2 K$)	3.6	2.1	2.0	1.7	1.6	1.5
Costs (£)						
Capital	143	154	173	209	162	193
Electricity	1140	656	624	531	499	468
Gas	329	189	180	153	144	135
Painting	90	90	90	90	90	90
Staining	180	180	180	180	180	180
Cleaning	893	893	893	893	893	893
Totals						
Electricity/Paint	2265	1793	1780	1722	1644	1644
Electricity/Stain	2355	1883	1870	1812	1734	1734
Gas/Paint	1454	1326	1336	1345	1289	1311
Gas/Stain	1544	1416	1426	1435	1379	1401

Al-clad Timber						
	4-16Air-4	4-16Air-e4	4-16Ar-e4	4-10Kr-e4	e4-16Air-4-16Air-e4	e4-16Ar-4-16Ar-e4
Capital	171	183	201	237	190	221
Electricity	1140	656	624	531	499	468
Gas	329	189	180	153	144	135
Painting	14	14	14	14	14	14
Staining	33	33	33	33	33	33
Cleaning	893	893	893	893	893	893
Totals						
Electricity/Paint	2218	1746	1732	1675	1596	1596
Electricity/Stain	2237	1765	1751	1694	1615	1616
Gas/Paint	1406	1279	1288	1297	1241	1263
Gas/Stain	1425	1298	1307	1316	1260	1282

Table 5.2 Life cycle costing of aluminium clad timber and timber windows at an Edinburgh location with 6 different glazing compositions with four different running options gas paint, gas stain, electricity paint and electricity stain - Commercial applications

Timber windows						Edinburgh
	4-16Air-4	**4-16Air-e4**	**4-16Ar-e4**	**4-10Kr-e4**	**e4-16Air-4Air-e4**	**e4-16Ar-4-16Ar-e4**
U-Value (W m^2-K)	3 6	2.1	2.0	1.7	1.6	1.5
Costs (£)						
Capitai	143	154	173	209	162	193
Electricity	1043	599	571	485	457	428
Gas	301	173	165	140	133	124
Painting	90	90	90	90	90	90
Staining	180	180	180	180	180	180
Cleaning	893	893	893	893	893	893
Totals						
Electricity Paint	2168	1737	1726	1677	1602	1604
Electricity/Stain	2258	1827	1816	1767	1692	1694
Gas/Paint	1426	1311	1321	1332	1278	1300
Gas/Stain	1516	1401	1411	1422	1368	1390

Al-clad Timber						
	4-16Air-4	**4-16Air-e4**	**4-16Ar-e4**	**4-10Kr-e4**	**e4-16Air-4-16Air-e4**	**e4-16Ar-4-16Ar-e4**
Capital	171	183	201	237	190	221
Electricity	1043	599	571	485	457	428
Gas	301	173	165	140	133	124
Painting	14	14	14	14	14	14
Staining	33	33	33	33	33	33
Cleaning	893	893	893	893	893	893
Totals						
Electricity Paint	2120	1689	1679	1629	1554	1556
Electricity/Stain	2139	1708	1698	1648	1573	1576
Gas/Paint	1378	1263	1273	1284	1230	1252
Gas/Stain	1397	1282	1292	1303	1249	1271

Table 5.3 Life cycle costing of aluminium clad timber and timber windows at a Manchester location with 6 different glazing compositions with four different running options gas/paint, gas stain, electricity paint and electricity stain - Commercial applications

			Timber windows			Manchester
	4-16Air-4	**4-16Air-e4**	**4-16Ar-e4**	**4-10Kr-e4**	**e4-16Air-4Air-e4**	**e4-16Ar-4-16Ar-e4**
U-Value (W m^2-K)	3.6	2.1	2.0	1.7	1.6	1.5
Costs (£)						
Capital	143	154	173	209	162	193
Electricity	938	539	513	437	414	385
Gas	271	155	148	126	119	112
Painting	90	90	90	90	90	90
Staining	180	180	180	180	180	180
Cleaning	893	893	893	893	893	893
Totals						
Electricity/Paint	2063	1676	1669	1628	1559	1561
Electricity/Stain	2153	1766	1759	1718	1649	1651
Gas/Paint	1397	1292	1303	1318	1264	1288
Gas/Stain	1487	1382	1393	1408	1354	1378
			Al-clad Timber			
	4-16Air-4	**4-16Air-e4**	**4-16Ar-e4**	**4-10Kr-e4**	**e4-16Air-4-16Air-e4**	**e4-16Ar-4-16Ar-e4**
Capital	171	183	201	237	190	221
Electricity	938	539	513	437	414	385
Gas	271	155	148	126	119	112
Painting	14	14	14	14	14	14
Staining	33	33	33	33	33	33
Cleaning	893	893	893	893	893	893
Totals						
Electricity/Paint	2016	1629	1621	1581	1511	1514
Electricity/Stain	2035	1648	1641	1600	1530	1533
Gas/Paint	1349	1245	1256	1270	1216	1240
Gas/Stain	1368	1264	1275	1289	1235	1259

Table 5.4 Life cycle costing of aluminium clad timber and timber windows at a Wales (southern part) location with 6 different glazing compositions with four different running options gas paint, gas stain, electricity paint and electricity stain - Commercial applications

			Timber windows			**Wales** (southern part)
	4-16Air-4	**4-16Air-e4**	**4-16Ar-e4**	**4-10Kr-e4**	**e4-16Air-4Air-e4**	**e4-16Ar-4-16Ar-e4**
U-Value (W m^2-K)	3.6	2.1	2.0	1.7	1.6	1.5
Costs (£)						
Capital	143	154	173	209	162	193
Electricity	873	513	489	416	391	367
Gas	258	149	142	121	113	106
Painting	90	90	90	90	90	90
Staining	180	180	180	180	180	180
Cleaning	893	893	893	893	893	893
Totals						
Electricity/Paint	1999	1651	1645	1608	1536	1543
Electricity/Stain	2088	1741	1735	1698	1626	1633
Gas/Paint	1383	1286	1297	1312	1258	1282
Gas/Stain	1473	1376	1387	1402	1348	1372
			Al-clad Timber			
	4-16Air-4	**4-16Air-e4**	**4-16Ar-e4**	**4-10Kr-e4**	**e4-16Air-4-16Air-e4**	**e4-16Ar-4-16Ar-e4**
Capital	171	183	201	237	190	221
Electricity	873	513	489	416	391	367
Gas	258	149	142	121	113	106
Painting	14	14	14	14	14	14
Staining	33	33	33	33	33	33
Cleaning	893	893	893	893	893	893
Totals						
Electricity/Paint	1951	1603	1597	1560	1488	1495
Electricity/Stain	1970	1622	1616	1579	1507	1514
Gas/Paint	1335	1238	1250	1265	1210	1234
Gas/Stain	1354	1257	1269	1284	1229	1253

Table 5.5 Life cycle costing of aluminium clad timber and timber windows at a London location with 6 different glazing compositions with four different running options gas paint, gas stain, electricity paint and electricity stain – Commercial applications

Timber windows						London
	4-16Air-4	**4-16Air-e4**	**4-16Ar-e4**	**4-10Kr-e4**	**e4-16Air-4Air-e4**	**e4-16Ar-4-16Ar-e4**
U-Value (W m^2-K)	3.6	2 1	2.0	1.7	1.6	1.5
Costs (£)						
Capital	143	154	173	209	162	193
Electricity	839	476	453	385	363	339
Gas	242	139	133	113	106	100
Painting	90	90	90	90	90	90
Staining	180	180	180	180	180	180
Cleaning	893	893	893	893	893	893
Totals						
Electricity/Paint	1965	1613	1609	1577	1508	1515
Electricity/Stain	2055	1703	1699	1667	1597	1605
Gas/Paint	1367	1277	1288	1305	1251	1276
Gas/Stain	1457	1367	1378	1395	1341	1366
Al-clad Timber						
	4-16Air-4	**4-16Air-e4**	**4-16Ar-e4**	**4-10Kr-e4**	**e4-16Air-4-16Air-e4**	**e4-16Ar-4-16Ar-e4**
Capital	171	183	201	237	190	221
Electricity	839	476	453	385	363	339
Gas	242	139	133	113	106	100
Painting	14	14	14	14	14	14
Staining	33	33	33	33	33	33
Cleaning	893	893	893	893	893	893
Totals						
Electricity/Paint	1917	1565	1561	1529	1460	1468
Electricity/Stain	1936	1584	1580	1548	1479	1487
Gas/Paint	1320	1229	1241	1257	1203	1228
Gas/Stain	1339	1248	1260	1276	1222	1247

Table 5.6 Annual heat loss of various glazing compositions at different locations and heat loss cost with electricity and gas heating systems

Window glazing	**4-16Air-4**	**4-16Air-e4**	**4-16Ar-e4**	**4-10Kr-e4**	**e4-16Air-4Air-e4**	**e4-16Ar-4-16Ar-e4**
U-Value (W m^2-K)	3.6	2 1	2.0	1.7	1.6	1.5
Annual Heat Loss (kWh)						
Aberdeen	274.9	158.2	151.0	128.0	120 4	112.9
Edinburgh	251.0	144.0	137.0	116.5	109.6	103.0
Manchester	226.2	130.0	124.0	105.3	99.8	92.9
Wales	210.5	123 8	118.0	100.4	94.4	88 5
London	202.4	114.7	109.3	92.9	87.5	81.8
Annual Electricity Cost (£)						
Aberdeen	15.1	8.7	8.3	7.0	6.6	6.2
Edinburgh	13.8	8.0	7.6	6.4	6 1	5.7
Manchester	12.4	7.2	6.8	5.8	5.5	5.1
Wales	11.6	6.8	6.5	5.5	5.2	4.9
London	11.1	6.3	6.0	5.1	4 8	4.5
Annual Gas Cost (£)						
Aberdeen	4.4	2.5	2.4	2.0	1.9	1.8
Edinburgh	4.0	2.3	2.2	1.9	1 8	1.6
Manchester	3 6	2.06	1.96	1.67	1 58	1.48
Wales	3.4	2.0	1 9	1.6	1.5	1.4
London	3.2	1.9	1.8	1.5	1 4	1.3

Table 5.7 Painting and staining costs

Timber windows are recommended to be painted externally on a 5 year cycle and stained after every 3 years. Internally, windows are painted normally after a life cycle of 10 years or more frequent depending upon the personal preferences, and staining can be carried out after every 5 years
Aluminium cladded windows do not require any external painting or staining maintenance. The powder coating paint on the aluminium cladding is stable enough to last over the studied life cycle of 40 years, hence externally it requires no painting maintenance.

YEAR	INTERNAL PAINT
0	2 5
10	3 36
2	4 52
30	6 7
TOTAL	**13 95**

YEAR	INTERNL STAIN
0	2 5
5	2 9
10	3 36
15	3 89
20	4 52
25	5 23
30	6 07
35	7 03
TOTAL	**33.00**

YEAR	EXTERNAL PAINT
0	5 75
5	6 67
10	7 73
15	8 96
20	10 39
25	12 04
30	13 96
35	16 18
TOTAL	**75.93**

YEAR	EXTERNL STAIN
0	5 75
3	6 2
6	6 7
9	7 5
12	8 2
15	8 96
18	9 79
21	10 7
24	11 69
27	12 77
30	13 96
33	15 25
36	16 67
39	18 21
TOTAL	**146 85**

TOTAL COST OVER LIFE-CYCLE OF 40 YEARS

TIMBER WINDOW

Painting £89.88
Staining – £179.85

AL CLAD TIMBER WINDOW:

Painting = £13.95
Staining = £33.00

Table 5.8 Annual cleaning cost over 40-year life cycle

ANNUAL COST:

Externally: £6 Window
Internally: £6 Window

Total annual cleaning cost /window = £12

YEAR	COST	YEAR	COST	YEAR	COST	YEAR	COST
0	12.00	10	16 13	20	21.67	30	29.13
1	12.36	11	16.61	21	22.32	31	30.00
2	12.73	12	17.11	22	23.00	32	30.90
3	13.11	13	17.62	23	23.68	33	31.83
4	13.50	14	18.15	24	24.39	34	32.78
5	13.91	15	18 69	25	25.13	35	33.77
6	14.33	16	19.26	26	25.88	36	37.78
7	14.76	17	19.83	27	26.66	37	35.82
8	15.20	18	20.43	28	27.46	38	36.90
9	15.66	19	21.04	29	28.28	39	38.00

Total cleaning cost over a life cycle of 40 years = £892.91

CHAPTER 6: COMPARISON OF WINDOW FRAMES

6.1 INTRODUCTION

Windows consist of two basic elements, frame and glazing unit. Frame is sometimes further divided into two parts, fixed frame and sash. The material used to manufacture the frame not only governs the physical characteristics such as frame thickness, weight, and durability, but it also has a major impact on the thermal performance of the window. Since the sash and frame represent from 10 to 30 percent of the total area of the window unit, the frame properties have significant impacts on the overall performance of the window.

Ideally a window frame should possess following characteristics.

Dimensional stability; a frame should expand and contract at the same rate as glass to prevent air leakage.

High strength; a frame should be strong enough to support glazing unit well, should provide high strength and rigidity to prevent the forced entry.

Low thermal conductivity; a frame should possess good thermal insulation, minimising the heat transmittance.

Weathering resistance; a frame should be well resistant to environmental/degradation factors such as humidity, temperature, chemicals, salt air and or acid rain etc.

Durability and maintenance; a frame should be durable and economical, maintaining satisfactory performance over the window service life

Windows, these days are available in a wide range of frame materials such as aluminium, PVC, timber and claddings of aluminium or PVC on timber, hybrid and composite, and fibreglass. Different frame materials have got their respective merits. This chapter analyses four different frame materials, i.e. aluminium, aluminium-clad timber, PVC and timber make, in terms of their production, energy consumption and environmental impacts, durability and service life, weathering performance and cost. A survey analysis has been carried out to assess the performance of the window types studied in actual service life The survey has been conducted with the help of local housing authorities, surveyors and architects within UK.

6.2 ENERGY & ENVIRONMENTAL IMPACTS

Environmental impacts associated with windows are due to the pollution resulting from the production

of constituent materials and the energy consumed. Material pollution relates mainly to pollutants in air, earth and water from the material itself and from the constituents of the material when being worked, during use as well as disposal at the end of their service life. The source of energy used can vary a great deal from country to country, for example, electricity used in different countries is produced from different resources such as nuclear power, fossil fuels and hydropower that lead to disparate environmental impacts.

The three main frame materials investigated, aluminium, PVC and timber (aluminium-clad timber windows being a composite of timber and aluminium are not as such a separate entity) generate some environmental loads during their production processes. Aluminium and timber, in this regard, have already been discussed in chapter 4. PVC is described in the following sections.

6.2.1 PVC production

PVC is normally produced from sodium chloride (salt) and natural gas or oil, as shown in Fig 6.1. Chlorine is produced by the electrolysis of salt solution, while the oil or gas undergoes a 'cracking' process to produce ethylene.

Ethylene dichloride is produced by the reaction of ethylene and chlorine, which then undergoes another cracking process to produce vinyl chloride monomer. Vinyl chloride, commonly referred as VCM (vinyl chloride monomer), is a gas at normal temperature and pressure. The by-product of converting EDC (ethylene dichloride) to vinyl chloride is hydrochloric acid.

This is then 'polymerised' – the molecules joined together – to produce a sludge which is centrifuged and dried to achieve polyvinyl chloride in the form of a white powder.

Because PVC is thermally unstable, stabilisers such as lead or organotins have to be added for virtually all applications. A host of other addit ves are necessary softeners, colouring agents, strengthening agents, flame retardants, biocides, lubricants, impact modifiers depending on the properties required in the final product.

Production of PVC is an energy intensive process. Energy value of PVC, as reported in different findings, is quite consistent, 84 MJ/kg by Berge (2001), 79 MJ/kg by lawson (1995) and 84 MJ kg by Buchanan et al (1994).

6.2.2 Disposal and recycling of frames

Ecology of building materials is very important in today's sustainability conscious world. Earth Summit 2002 has emphasised the need of environmentally sound materials that cause less pollution and possess the tendency of recyclability or safe disposal, urging all the countries to;

Prevent and minimise waste and maximise reuse, recycling and use of environmentally friendly alternative materials, with the participation of government authorities and all stakeholders, in order to minimise adverse effects on the environment and improve resource efficiency (ES-2002).

Recycling of materials, rather than manufacturing from new raw materials, can considerably reduce the environmental impacts. It helps cutting down the energy consumption and waste generation during extraction or production phases of materials. Recycleability of materials depends upon their purity, i.e., recycling of composites or multiple materials is quite complex.

Disposal recycling of aluminium and timber has been discussed in detail in chapter 4, some of the key points relevant to this section are;

- Aluminium is easily recycled, requiring only 5-7% of the energy as required for primary aluminium (Berge, 2001, O'Connor, 2000 and EAA).
- Recycling avoids the energy extensive processes, extraction of basic Bauxite, and the use of other chemical materials involved, contributing to a 95% reduction in greenhouse gases emission (Craighill et al 1996 and IAI).
- Aluminium windows can be recycled to produce windows again without any compromise on quality.
- Timber windows at the end of their service life can be disposed off through land-filling or serving as fuel. They can also be down-cycled.

Aluminium-clad timber window frames at the end of their service life can be broken down into its basic ingredients, aluminium and timber which can be treated in similar pattern as described above.

PVC windows are normally disposed off through land-filling or incineration. PVC is the major contributor to chlorine in incinerators, which leads to the production of dioxin - one of the most toxic synthetic chemical. Additives such as phthalates and heavy metals, can leach out of landfilled PVC and may contaminate ground water. Waste management of PVC and the resulting toxicity is a point of concern as highlighted in the Green Paper on 'Environmental Issues of PVC' produced by the

Commi ion of the European Communities (Green Paper, 2000) and has been a knowledged by the UK Department for Environment, Food & Rural Affairs (DEFRA).

Recycling of polymer products require sorting of the waste into generic materials. The quality of the recyclate depends heavily on the level of impurities such as other polymer or reinforcement materials. The composition of the PVC, i.e. which additives have been used, is also important. PVC waste streams are a complex mixture of materials from a variety of sources. This makes recycling technically and economically very difficult since the right balance of additives in the recycled PVC cannot be achieved from the recyclate consisting of various formulations, and it can only lead to a lower quality PVC material down-cycled. Recycled PVC reduces GWP by 66% than the virgin PVC. Table 6.1 as extracted from the work of Craighill et al (1996) shows that recycling of PVC is economically expensive choice, as also indicated by other resources such Professional Engineering (PE, 2002) and Greenpeace.

6.2.3 Embodied energy

Embodied energy of aluminium clad timber and timber windows have been thoroughly investigated as discussed in chapter 4. Aluminium and PVC windows have not been as such investigated in this work. However a few references about PVC and aluminium windows have been found in literature, for example, Lawson (1995) has provided energy values of 4115.7 MJ, 1837.6 MJ and 506.5 MJ for aluminium, PVC and timber windows, respectively. Berge (2001) does not provide quantified energy values of windows, however, reports that PVC and aluminium windows consume 6 and 10-30 times more energy, respectively, than timber windows. BRE as referred by English Heritage (Energy saving, 1994), also has conducted a study showing that the energy consumption of PVC windows is three times more than softwood windows. It is therefore concluded herein that aluminium windows are the most energy expensive. The energy value for a double glazed Ar filled (1.2m ×1.2m) timber window, quantified in present research, is 738 MJ, which is quite different to value provided by Lawson (1995). Work done by Lawson does not provide much details of his LCA boundaries, however, few things are quite clear that he does not takes into account the energy involved in whole range of processing. The size of windows investigated is also different (1.7m ×1.2m) in Lawson's work while wastage of materials during production process has also been excluded. It is therefore obvious that this difference of values is due to different LCA boundaries and depth of investigation However, one of the conclusions that can be drawn from Lawson's work is the relative ratio of timber, PVC and aluminium windows that is respectively 1.3.6.8 1. Taking the energy values obtained in present work for the alum nium clad timber and timber windows as the base, and us ng relative ratio of energy values provided by Lawson (1995), energy values for aluminium and PVC windows can be worked out, equal to 5978 MJ, 2657 MJ, respectively (Fig. 6 2).

6.2.4 Environmental impacts

Out of the studied frame materials in this work, aluminium has the highest environmental impacts, due to its energy extensive production and the resulting pollutants. Timber windows come from a sustainable source since timber is now being considered as a renewable material due to well or anised forest management systems. Processing and production of timber frames do not impose any significant loads on environment.

Aluminium clad timber windows have similar environmental characteristics as the timber windows except the added loads of aluminium cladding.

PVC, in its production is energy extensive and possesses large amounts of environmental impacts throughout its life cycle. Production of PVC releases a number of toxic elements as shown in Fig 6.1. Disposal of PVC windows, at the end of their life, generates huge environmental impacts whether they are down-cycled, land-filled or incinerated.

A study carried out by Lawson (1995) has produced similar results, showing that GWP for a reference timber, PVC and aluminium window frames is in a ratio of 1:11:26 respectively. Citherlet (2000) has analysed environmental impacts of different window designs. The results show that aluminium and PVC window frames have higher environmental impacts as compared to aluminium clad timber and timber windows, while the latter two are in a close proximity in terms of their environmental impacts, as shown in Figs. 6.3 (a), 6.3 (b) and 6.3 (c). Berge (2001) has provided environmental loads of the three basic materials involved in studied window frames, i.e. aluminium, PVC and timber (Table 6.2). Statistics provided by Berge have also highlight the greater affiliated loads of aluminium and PVC as compared to timber. It can therefore be concluded that aluminium and PVC windows have larger amounts of environmental impacts while aluminium clad timber and timber windows produce less impacts on the environment.

Another important issue regarding sustainability of window frames is the availability of natural resources. Table 6.3 shows that timber has the clear advantage being the renewable source. The amount of aluminium resources available, is not alarming as such, since aluminium is a completely recyclable material and virgin aluminium is also available for a considerable future production. PVC resources, as it comes from hydrocarbons, are left for a limited time. Berge (2001) and Lawson (1995) have reported that oil resources left are only for 40 and 50 years, respectively. Figures 6.4, 6.5 & 6.6 show the flow diagrams of the LCA of aluminium, PVC and timber windows, re pectively LCA diagram of aluminium clad timber window has already been provided in chapter 4.

6.3 DURABILITY AND SERVICE LIFE

Durability and service life, in their general meaning have been highlighted earlier in chapter 5. These are very important characteristics that determine the worth of any product In this section window frames are discussed regarding these characteristics. Any effective estimation of the durability and life span should always be accomplished with the material and service conditions specifications as also indicated by Westberg (2001). An important aspect of durability and service life of windows besides the quality and design, is the degree of care taken throughout their service life and their exposure conditions. Lack of maintenance and after-sale care can lead towards increased wear and tear, reducing window's operational life. The quality of material plays an important role in determining durability, especially in the case of timber and PVC windows.

Estimations of the life expectancies of windows result in different findings depending upon the purpose required. In theory, components are capable of lasting for a very long time. In practice however, the life expectancy is frequently much shorter for a variety of reasons, as highlighted in section 5.2.4. Service life of a window can be justified by its effectiveness in terms of structural, environmental, security, aesthetic or economic performance.

The results of the survey carried out have provided the life expectancies of windows. Survey results have been summarised on the basis of feedback received from 25 different organisations. It has been observed that housing authorities normally prefer a given window type. In some cases they have established their own window manufacturing units and their perception of durability and performance of windows is choice driven, normally under-estimating other window designs. Survey feedback show that PVC is the most widely used type of window, followed by timber, aluminium and aluminium clad timber respectively. Summarised results reveal the life span of more than 43.6, 39.6 and 46.7 years for the aluminium, timber and aluminium clad timber windows, respectively. PVC window life is estimated to be in the region of 25-30 years, as shown in Table 6.4.

Worcester City Council provides life span of aluminium, PVC and timber windows equal to 50-60 years, 30 years and more than 40 years respectively (WCC, 1990). Another study by Citherlet (2000) provides the life span for aluminium, PVC, timber and aluminium clad timber frames, equal to 45, 30, 45 and 45 years respectively. Another service life report by HAPM (1996) provides expected life of 35 years for aluminium, and timber windows, and 25 years for PVC windows.

Results of the survey and other three studies (from WCC, 1990, Citherlet, 2000 and HAPM, 1996) provide quite identical figures for windows life; aluminium, aluminium clad timber and timber windows are considered to be durable enough to last sufficiently long - more than 40 to 45 years (the maximum life expectancy limit for these windows is not defined anywhere) while PVC is considered to have a limited life and general perception of their maximum life is up to 30 years. Table 6.5 summarises the life expectancy results of the present survey and above mentioned studies.

6.3.1 Weathering

Durability and life span of windows also depend upon their weathering performance. Weathering characteristics of window frames have already been discussed in detail in chapters 2 and 3 which reveal that uncoated aluminium windows can receive corrosive attacks under extensive conditions despite their natural resistance against corrosion. Surface treatments, anodising and powder coating, provide excellent weathering resistance to aluminium windows. Timber windows can also receive environmental impacts if not properly surface treated. With regular coatings, weathering performance of timber windows can be improved. PVC windows are sensitive towards heat and UV radiation of sunlight. Using better stabilisers, PVC can also improve its resistance against these factors. Aluminium-clad timber windows have been found to exhibit good weathering performance as compared with other windows.

6.4 MAINTENANCE AND REPAIR

Maintenance of windows can be generally classified as following.

- Planned; painting and cleaning
- Unplanned; responding the faults - replacement of window hardware, i.e. ironmongery and weather stripping

Since this study is focussed on the frame materials, the maintenance issues discussed are only those belonging to frames of the windows. Unplanned maintenance - faults in the window hardware is a feature that is common in all types of frames, it is therefore not dealt with here.

Aluminium windows are widely considered to be requiring low maintenance. Aluminium windows can be used without any surface treatment, eliminating the routine maintenance costs apart from cleaning for aesthetic reasons as stated by European Aluminium Association (EAA). However, for increased surface protection and durability, aluminium windows are usually recommended to be delivered with a protective coating, suitable for the conditions of use (Hornbostel, 1978). The frequency of repainting depends upon the coating specifications. Anodising and powder coating finishes last for a fairly long duration, for example, Furneaux (2001) provides evidence of anodised treatment of aluminium to last well above 20 years even under aggressive environmental conditions.

Maintenance of PVC frames is quite a debated issue. PVC windows manufacturers claim their products to be maintenance free ruling out any need for proper maintenance efforts. This characteristic of PVC windows is highlighted the most for marketing by the manufacturers. There are valid arguments on the other side as well, advocating that PVC windows are not maintenance free and do require regular cleaning in order to maintain their appearance as indicated by Carmody (1996), English Heritage (1994) and Kent (in a web article). Scratching can be a predominant surface damage of PVC windows. Scratches are caused by airborne particles whose hardness is greater than the PVC material. Shallow scratches can be rubbed out with light steel wool, fine emery cloth, or soft scrub cleaner. Scratches can also be removed using appropriate solvents. HAMP (1996) recommends the cleaning of PVC windows with non-alkaline detergents after every six months. PVC windows are not easy to be repaired in case of damage, and require special skills. WCC (1990) reports that repair of damaged PVC frames is unsatisfactory.

Maintenance and repair characteristics of aluminium clad timber and timber windows have been discussed earlier in chapter 5.

6.5 PRICE COMPARISON

Price comparison of windows is challenging due to a number of factors such as the quality of materials used, extra functionality of windows, brand names and marketing factors such as, discounts and incentives.

Quality of material used is quite consistent in case of aluminium windows since there are mainly two types of aluminium alloys used for windows, 6061 and 6063, and they both have standard compositions. In timber windows, quality (species) of timber used and pre-treatment carried out affects the price. Additives used in PVC differ in terms of cost. Since there is not any standard formulation of PVC it can be made in numerous formulations - its cost is driven by the types of additives used, depending upon the composition adopted by the manufacturer. It can therefore be concluded that the cost of PVC windows is somehow a quality driven factor.

General perception about windows price is that PVC windows are cheaper than aluminium and timber ones. On the other hand few studies carried out by various organisations such as , English Heritage (Energy savings, 1994), National Housing Federation (Standards in Quality and Development, 1998) and Carlisle City Council (1998), have shown that timber (softwood) windows are more economical than PVC windows, while aluminium windows remain as the most expensive choice. A cost comparison provided by Worcester City Council (WCC, 1990) shows that PVC windows are the most expensive choice, providing the relative cost of one square meter, equal to £140.2, £144 and £130 for aluminium, PVC and timber windows respectively. Aluminium clad windows are normally slightly more expensive than the timber ones. Price comparison therefore, still, remains quite involved to categorically bench mark the windows.

6.6 FUNCTIONAL PERFORMANCE

Aluminium windows are light weight and strong. Being made of a metal, these windows are rot-proof, do not swell, split or warp. Since aluminium is easily extruded, it can be formed into small, strong shapes which can be made as complex as necessary. High strength and rigidity of aluminium makes it a favourable window material in high-rise buildings, as highlighted by EAA. The major disadvantage of aluminium as the frame material is its high U-value, thermal conductance, that can result into energy loss and condensation under the cold conditions. Thermal insulation of aluminium windows can be reduced by splitting the frame into interior and exterior parts and incorporating a thermal break/insulation between the two parts.

PVC window frames have good insulating properties, do not require painting and have good moisture resistance. They have low maintenance requirement and require cleaning to maintain their aesthetic appearance. Durability and service life of PVC windows differ a lot, depending upon their formulation, i.e. nature and composition of additives as also indicated by Holladay (web article). The major draw back of PVC windows is their sensitivity towards UV, excessive temperature and strong light levels.

Timber is the traditional window frame material, because of its availability and ease of milling into complex shapes required to make windows. Timber frames have good thermal resistance and are favoured in many residential applications because of their appearance and traditional place in house design Timber frames are susceptible to intensive weathering impacts as well as biological attacks as discussed in chapter 2, however a well built and well maintained timber window can last considerably long, even hundreds of years. Surface treatments have helped increasing weathering resistance and durability of timber frames.

Aluminium clad timber windows are comparatively newer in the market. They, possessing the characteristics of timber windows with the added advantage of aluminium cladding, not only to improve its weathering performance and aesthetic appearance but also to reduce the maintenance cost, are becoming an attractive option.

6.7 MARKET SCENARIO

Over the last few years the European window market is in a period of stagnancy. Since the 1990s Europe's window market has grown steadily up to a peak of 88.5 million installed window units in 1999. In 2000 there was a 0.8% fall and in 2001 a growth of 0.4%. Germany is the largest shareholder of Europe's window market followed by UK, Spain and France. Different national architectural styles lead to different preferences regarding the construction material used. In Germany, Austria, Great Britain and Ireland, in 1999 over half of all windows were of PVC design. In contrast, timber windows dominate in the Benelux states, Scandinavia, and Eastern Europe. In Spain, Portugal, Italy and Greece aluminium or aluminium-clad timber windows are preferred. For example, in Spain aluminium windows have a market share of 74 %. In Europe as a whole, in 1999, PVC windows had a share of 38 2 %, timber 31 4 % and aluminium windows 30 4 (Aluminium, 2001). Another report by Bag haw (2001), specifically indicates that Germany has a PVC share of 52 , timber 27 , aluminium 18 while 3 % for aluminium clad timber windows. Although PVC windows are becoming more widely used, their market share is growing less rapidly than before. There are some fluctuations noted in PVC ma ket share due to environmental concerns of PVC, as indicated by Bagshaw (2001) and Plastic and Rubber Weekly (P&RW, 1998).

Aluminium windows are preferred by architects in the commercial and non-residential sectors. Timber windows are a preferred choice in residential construction. Timber windows are preferred in many cases by people owning their properties and in buildings classified as historical monuments. PVC windows are used primarily in the replacement market in housing schemes or in multiple family housing.

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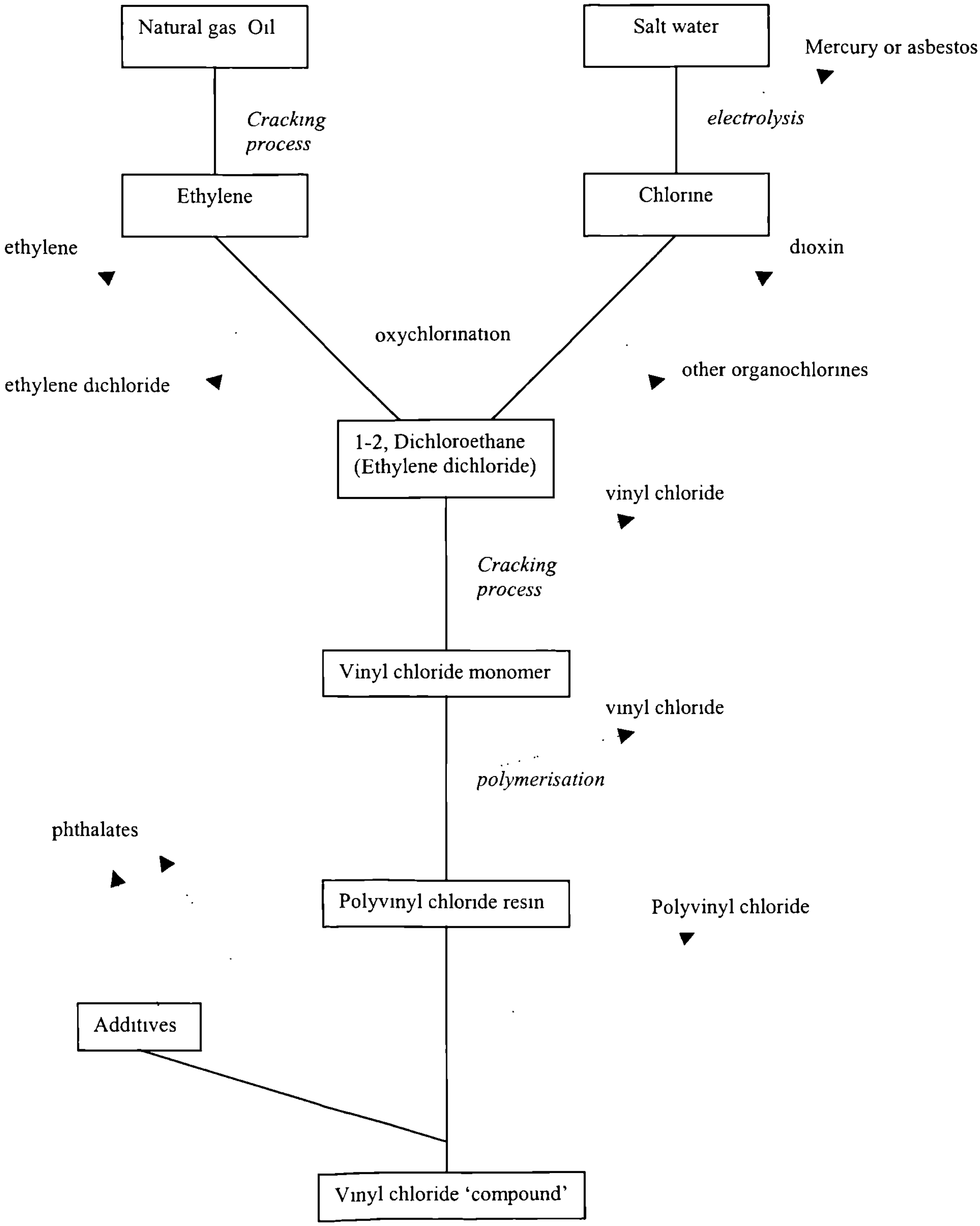

Fig. 6.1 PVC production and associated emissions

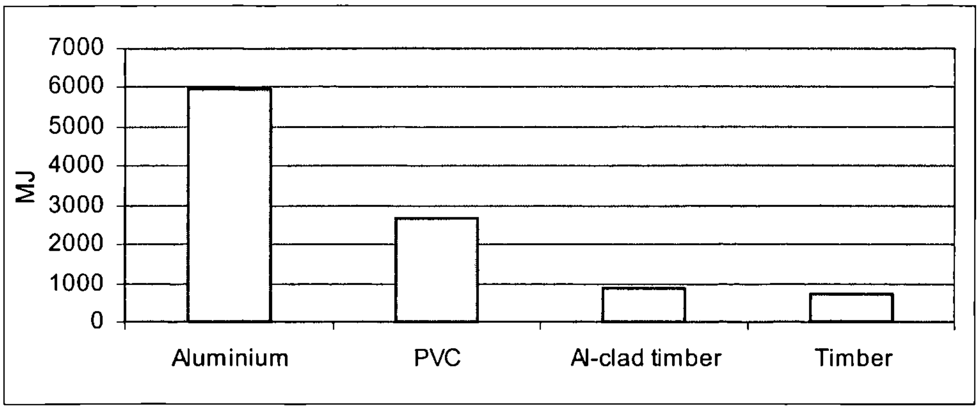

Fig. 6.2 Embodied energy comparison of different window designs

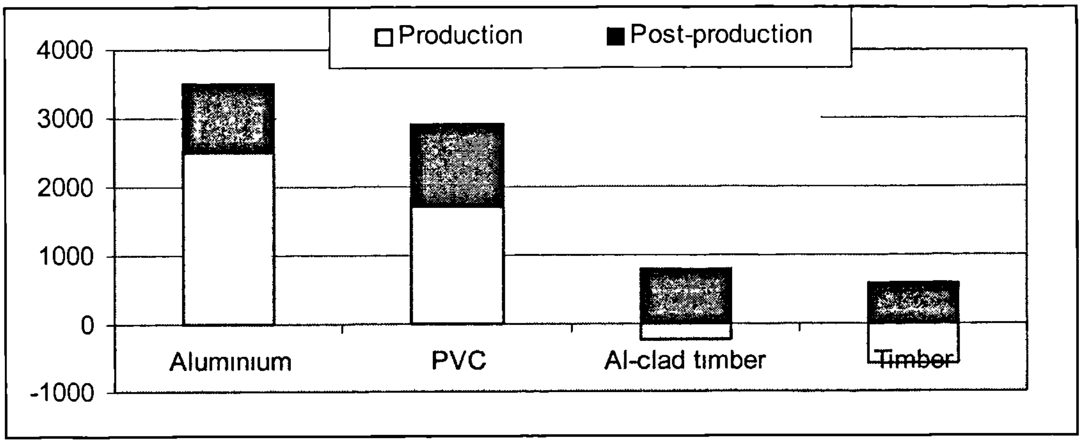

Fig. 6.3 (a) Global Warming Potential for different window frames - GWP[g eq. CO_2/m^2]

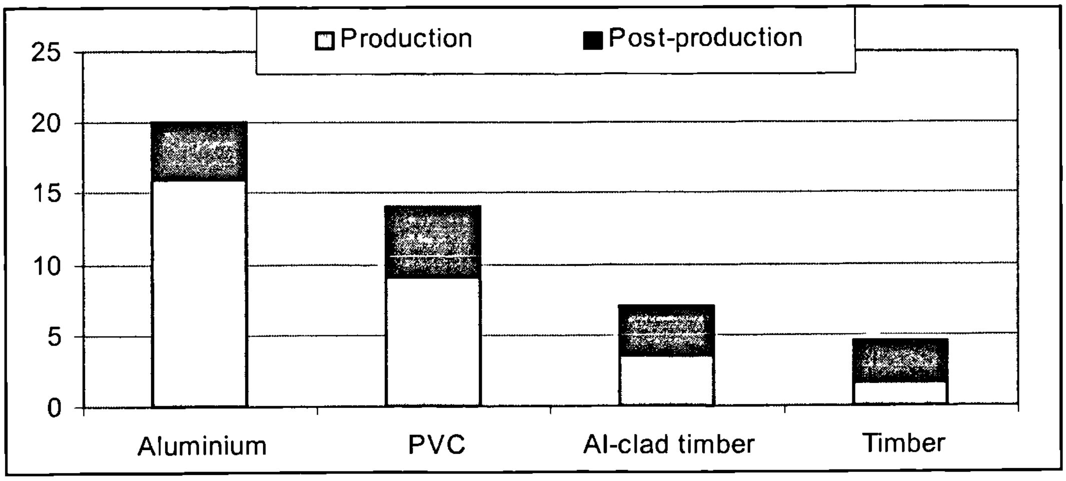

Fig. 6.3 (b) Acidification potential for different frames – AP [g eq. SO_x m2 year]

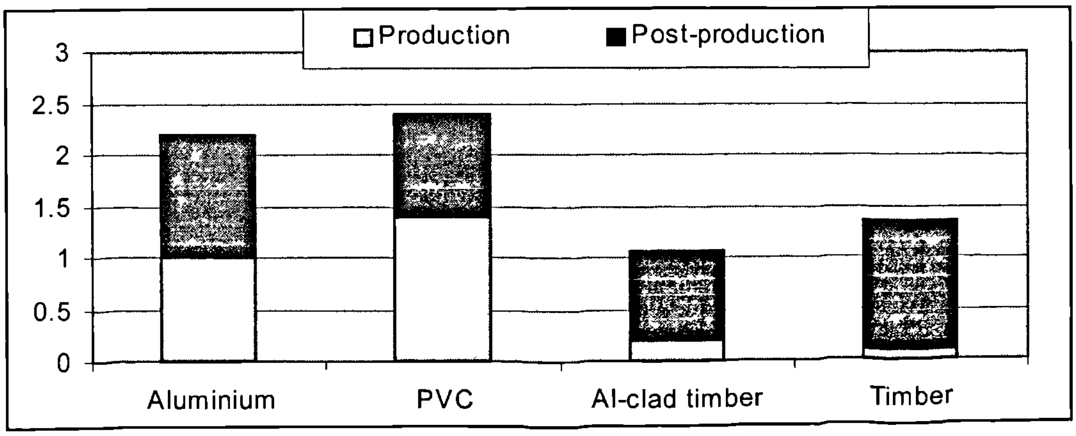

Fig. 6.3 (c) Photochemical ozone creation process for different frames POCP [g eq. C H_4/m^2 year]

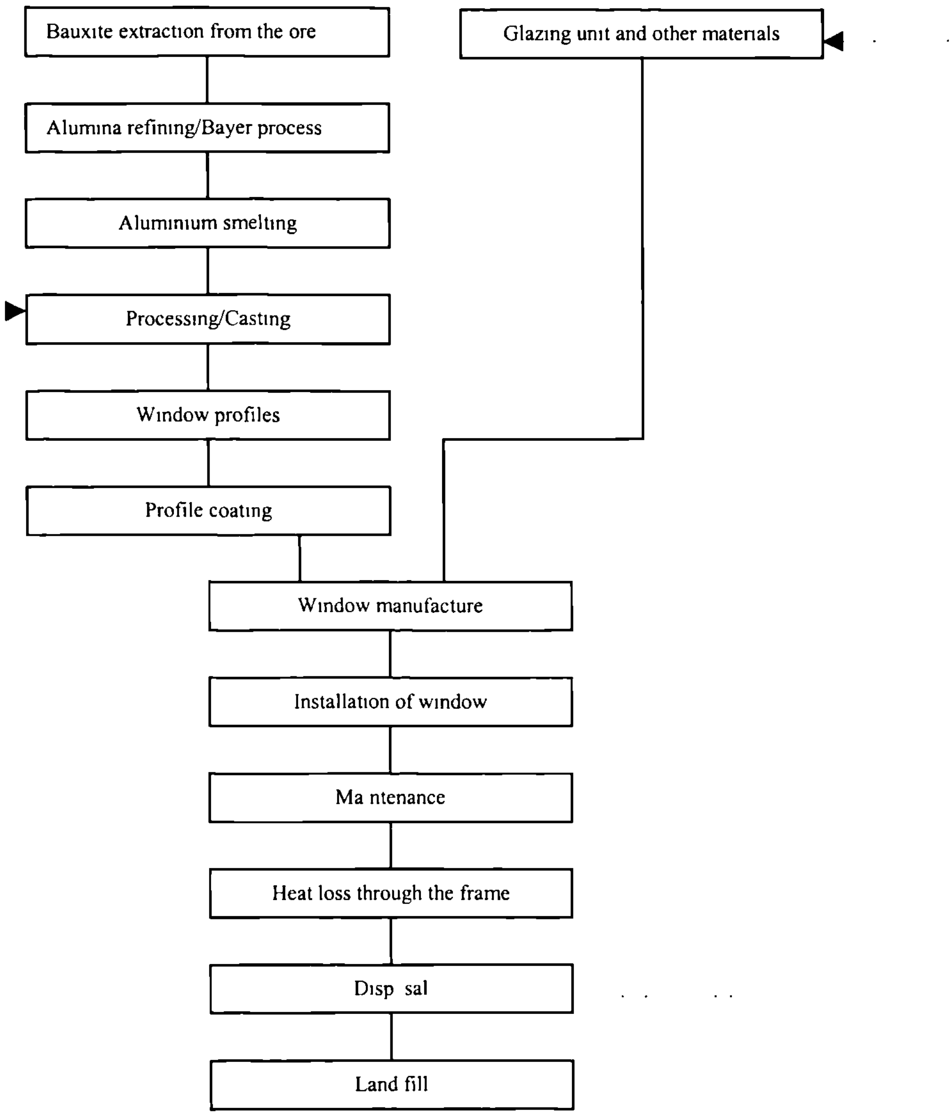

Fig 6.4 LCA of an aluminium window

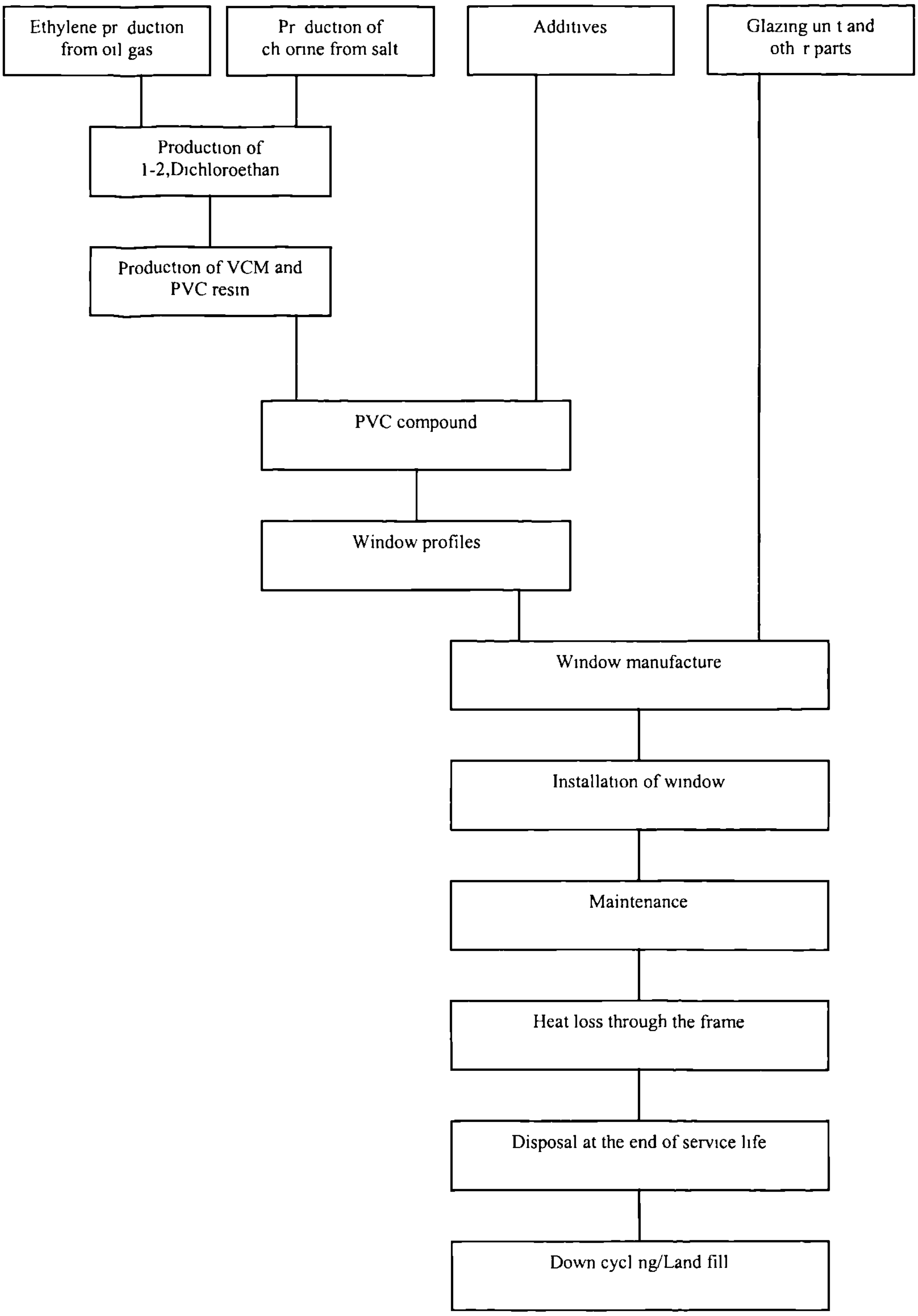

Fig. 6 5 LCA of a PVC window

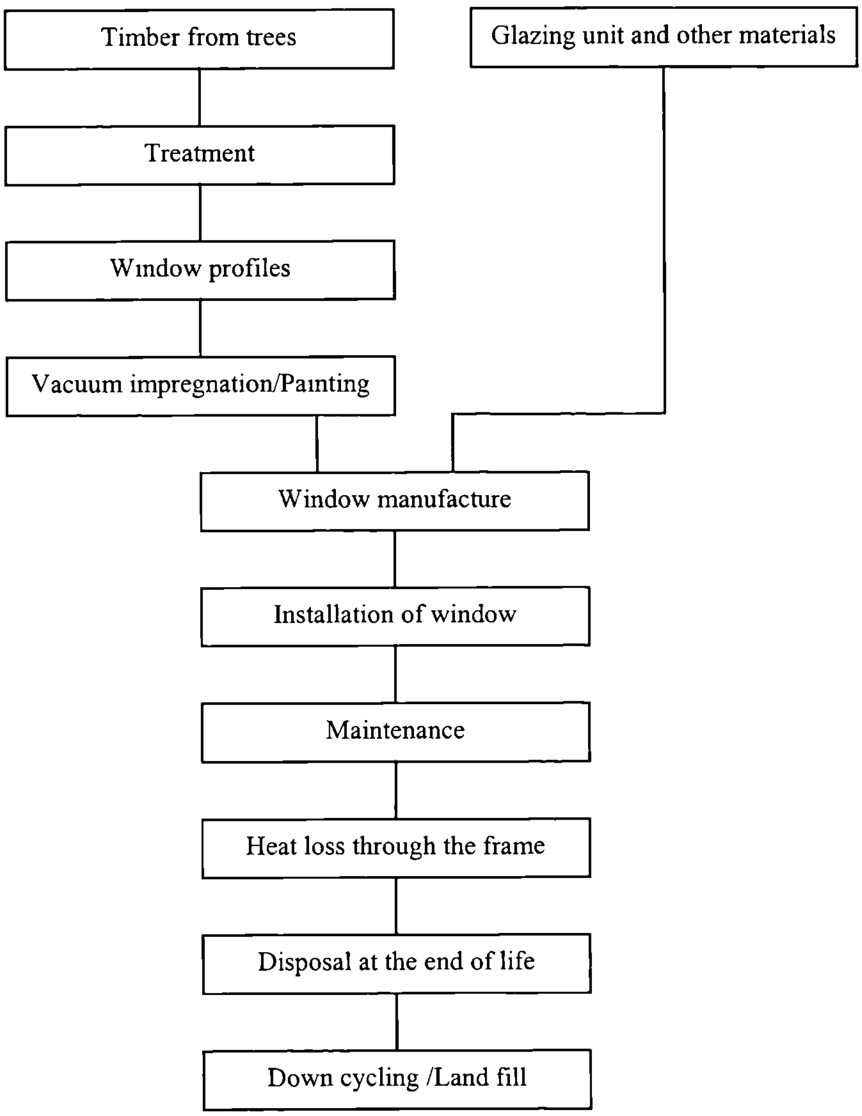

Fig. 6.6 LCA of a timber window

Table 6.1 Economic evaluation of external costs (£ tonne)

Material	Waste disposal £ t	Recycling £ t	Net benefit from recycling £ t	Net benefit excluding congestion £/t
Aluminium	1880.27	111.41	1768.86	1771.84
Glass	254.78	67.20	187.58	189.96
PVC	7.46	11.55	-4.10	-1.57

Table 6.2 Environmental impacts affiliated with different window frame materials in Scandinavia and Europe

Material	Scandinavian peninsular			European continent		
	GWP g/kg	AP g/kg	POCP g/kg	GWP g/kg	AP g/kg	POCP g/kg
Aluminium	1900	13	3	11102	60	119
PVC	700	13		1400	13	0.5
Timber	40	0.6	0.8	116	1	1

GWP Global warming potential in grams CO_2 equivalents

AP – Acid potential in grams SO_2 equivalents

POCP Photochemical Ozone Creation Potential in grams NO_x

Table 6 3 Natural resources available for the window frame materials

Material	Number of years left as reserves
Timber	Renewable
PVC	40
Aluminium	220

Table 6.4 Survey analysis results

Window (frame type)	Estimated service life (years)			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

Table 6.5 Surveyed service life of windows compared with other estimates from Citherlet (2000) , HAMP and Worcester City Council (WCC, 1990)

Window type	Life span (years)			
	Survey	Citherlet	HAMP	WCC
Aluminium	43.6	45	35+	50-60
PVC	24.1	30	25	30
Timber	39.6	45	35+	40+
Aluminium clad timber	46.7	45		

CHAPTER 7: CORROSION CHARACTERISTICS OF Al - SiC (Cu COATED) MMC

7.1 INTRODUCTION

Metal matrix composites (MMCs) are materials that contain metal as the matrix (normally the major constituent). MMCs are important structural materials used in the aerospace, automotive, construction and leisure industries because of their improved specific strength, stiffness and wear resistance as compared to monolithic alloys, as highlighted by Knight (1987), Davidson et al (2000), Derby (1995) and Hall et al (1994).

Presented work in this field examines Cu coated silicon carbide (SiC) particulates reinforced into 6061 aluminium, produced through a powder metallurgy (solid state) technique. The SiC reinforcement is copper coated to improve the bonding between the matrix and the reinforcement, and also to enhances the mechanical properties of the composite. However, there were concerns regarding reduced corrosion resistance of the MMC (Cu coated SiC in Al matrix) due to the introduction of Cu. Al-SiC MMC has the tendency to serve as the window hardware material due to its attractive mechanical characteristics. This work aimed to study impacts of Cu coating on the corrosion behaviour of this particular composite. Al-SiC MMCs have been produced with and without Cu coating on the SiC. Different accelerated tests have been performed at Otto-Von-Guerecki University, Germany, to carry out corrosion investigations. This chapter provides a brief introduction to composite and MMC materials, fabrication of Al SiC MMC (both with Cu coated and uncoated SiC) samples and an analysis of any adverse impacts of Cu coating on corrosion behaviour of MMC. The accelerated testing programme as discussed in chapter 3, has been extended to investigate the corrosion behaviour of this particular MMC.

7.2 COMPOSITE MATERIALS

Composites are formed by combining two or more materials that have quite different properties. The different materials work together to give the composite unique properties, but within the composite different materials can be identified they do not dissolve or blend into each other.

Hull (1981) describes the following three main features a composite possesses.

- It consists of two or more physically distinct and mechanically separable materials.
- It can be made by mixing the separate materials in such a way that the dispersion of one material in the other can be done in a controlled way to achieve optimum properties.
- The resulting properties are superior, and possibly unique in some specific respects, to the properties of individual components.

The three basic entities in a composite material are matrix, reinforcement and the interface between them. These also determine the characteristics of the composites as discussed below.

- *Matrix*

Composites have two (or more) chemically distinct phases on a microscopic scale, separated by a distinct interface. The constituent that is continuous and is often but not always, present in the greater quantity in the composite is termed the matrix. The normal view is that it is the properties of the matrix that are improved on incorporating another constituent to produce a composite. A composite may have a ceramic, metallic or polymeric matrix; the mechanical properties of these three materials differ considerably. The matrix binds the reinforcement together and enhances the distribution of applied loads within the composite.

- *Reinforcement*

The second constituent is referred to as the reinforcement, as it enhances or reinforces the mechanical properties of the matrix. The reinforcement is the main load-bearing phase of the composite and provides enhanced strength and stiffness. In most cases the reinforcement is stronger, harder and stiffer than the matrix.

- *Interface*

The interface is the region of significantly changed chemical composition that constitutes the bond between the matrix and reinforcement for transfer of loads between these members of the composite structure (Metcalfe, 1974). In some cases a distinct phase, produced by a reaction between the matrix and reinforcement, exists at the reinforcement-matrix interface. In other instances the interface can be viewed as a planer region of only a few atoms in thickness across in which there is a change in properties from those of the matrix to those of the reinforcement. There are several bond types that can develop between the matrix and reinforcement, e.g. mechanical, electrostatic and chemical.

The nature of the interface has a strong influence on the properties of the metal matrix composite. Strengthening in the composite by the reinforcement is dependent on the strength of the interfacial bond between the metal and the reinforcement. The properties such as stiffness, fracture toughness, fatigue, coefficient of thermal expansion, thermal conductivity and creep are also affected by the nature of the interface

Another factor that influences the fabrication and properties of composites is the proportion of the matrix and the reinforcement. The proportion can be expressed either via weight fraction (w) or volume fraction (v), as described under.

Volume fraction

$v_f \quad V_f/V$ and $v_m \quad V_m/V_c$

Weight fraction

$w_f \quad W_f/W_c$ and $w_m \quad W_m/W_c$

where the subscripts m, f and c refer to matrix, fibre (or reinforcement) and composite respectively.

The shape, size, orientation and distribution of the reinforcement and various features of the matrix such as grain size, also affect the properties of composites. These together with volume fraction, constitute what is called the microstructure of the composite as described by Schwartz (1997) and Matthews (1995).

7.3 METAL MATRIX COMPOSITES

Generally composites are divided with respect to matrix type into following;

- Metal Matrix Composites (MMCs) composed of a metallic matrix
- Polymer Matrix Composites (PMCs) composed of a polymer matrix
- Ceramic Matrix Composites (CMC) composed of a ceramic matrix

The pre ent work deals with MMCs and these are described below in detail.

Metal matrix composites are metallic materials reinforced with continuous or discontinuous fibres, or whiskers or particulates. The matrix is a monolithic alloy (usually a low-density non ferrous alloy), and the reinforcement consists of high performance carbon, metallic, or ceramic additions. The volume fraction of reinforcement varies from 10-60 as highlighted in numerous studies such as Callister (1999). The greatest advantage of composite materials is strength and stiffness combined with lightness. By choosing an appropriate combination of reinforcement and matrix material, manufacturers can produce properties that exactly fit the requirements for a particular structure for a particular purpose. The density of most aerospace MMCs is about 1 3 that of steel as reported by Schoutens (1985). Thus, their spec fic strengths and stiffness are high. Schoutens (1985) states that these properties are important to spacecraft and aerospace applications because of the potentially very high reduction (25 50) in wei ht. Their high temperature strength retention is important, thus making them suitable for diesel and aircraft engines. The wide variety of MMC fabrication methods can be conveniently classified into one of the three categories; solid state, liquid state or spray deposition as also indi ated by Schoutens (1985). The selection of a fabrication process d pends on several factors, according to Knight (1987), the material to be processed, the size and design of product, the number of products and the rate of production are a few of the consideration.

Compared with non-reinforced metals (i e. monolitic material), MMCs have the following main properties

- higher specific strength
- higher specific stiffness
- improved creep resistance
- improved wear resistance
- poorer toughness
- poorer ductility
- more complex production routes
- more expensive production routes

7.3.1 Powder Metallurgy

This is the process of producing components from powders, mainly metallic in character, incorporating non-metals, metallic compounds or chemical additions in various proportions. Basically the process consists of pressing compacting the powder within dies followed by heating or sintering of the powder compact, usually under controlled atmosphere at a temperature below the melting point of the metal or alloy. By this means a porous to dense product is obtained having the required shape and size and the mechanical properties to fulfil the component's function; where such a basic process does not produce the required characteristics, various special processes or modifications may be introduced. General powder metallurgy process involves several stages, for example;

- powder production
- selection of powder
- powder conditioning
- blending
- pressing or compaction
- sintering
- further processing
- testing and inspection

The required physical and chemical characteristics of the powder may be produced by a variety of methods. These include both mechanical and physico-chemical treatment of either the solid, liquid or gaseous metal to convert it to powder. The mechanical process include machining, crushing, milling, shotting and atomising; the chemical ones include electrolysis of solutions or fused salts, thermal decomposition, acid disintegration, condensation and chemical displacement. The choice of powder affects not only the final characteristics of the product but also impacts the filling, compacting and sintering processes. The particular production method chosen controls the characteristics of shape, size, distribution, purity, surface conditioning and porosity of the individual particles. Powder immediately after production, may not have the necessary physical or chemical characteristics for use. Any defects may be overcome by mechanical, thermal or chemical treatments or alloying. Fig. 7.1 shows the complete route of powder metallurgy fabrication process.

7.3.2 Reinforcement coating

Coating of the reinforcement is one of the successful techniques adopted to prevent adverse interfacial reaction and enhance the wetting of the reinforcement. Different types of coatings given to reinforcements are metallic, ceramic, bilayer and multilayer coatings containing metals and/or ceramics, and are system-specific. The various coating techniques adopted aim at attaining a better, uniform and thin layer coating without degradation of the reinforcement properties. Copper and nickel are the important metallic coatings used to coat the fibres. There are various metallic coating techniques such as cementing, electroless and electrolytic processes.

7.4 Al-SiC (Cu coated) MMC

Among the various matrix materials available, aluminium and its alloys are widely used in the fabrication of MMCs. This is because of the fact that they are light in weight, economically viable, amenable for production by various processing techniques and possess good strength and corrosion resistance. The Al-SiC MMC, possessing improved strength and wear resistance, find potential applications as structural elements in automotive and aerospace industries. However there are some drawbacks affiliated with it such as low temperature ductility and reduced toughness. The cause of these problems is believed to be related to the interface structure and processing factors, as indicated by Rajan et al (1998). The reaction between SiC and liquid Al during processing cause significant degradations in properties of the composites. In order to prevent the degradation of SiC (particles, whiskers or fibres) and improve wettability, various treatments and coatings have been attempted (Rohatgi et al 1993, and Kobashi et al, 1993, as reported by Rajan et al (1998). The copper (Cu) coating of silicon carbide (SiC) helps developing a strong and ductile bond between Al and SiC, during sintering process, through formation and flow of Al-Cu liquid eutectic into porous areas.

7.5 PREPARATION OF TEST SAMPLES

The sequential steps carried out in preparation of MMC samples are shown in Fig. 7.2 and are discussed below.

7.5.1 Composition and weighing

The Al SiC MMC has following basic constituents

- Matrix 6061 aluminium alloy 90 % by mass in MMC

Particle size 75μm

Density 2.68gm/cm^3

- Reinforcement SiC 10 % by mass in MMC

Particle size - 23μm

Density 3.21gm/cm^3

Both the Al and SiC powders were weighed on a digital balance shown in Fig. 7.3.

7.5.2 Ultrasonic Cleaning:

The SiC particles (reinforcement) were cleaned ultrasonically to remove any impurities. They are cleaned using a solution propan-2-ol inside an ultrasonic bath. This generates vibrations which dislodge impurities from the surface of the SiC. The SiC was filtered afterwards and dried in oven at 80 C for 2 hours.

7.5.3 Acid Cleaning (etching)

The second treatment applied to SiC was acid cleaning (etching). This further prepares the surface of the particles for direct bonding with matrix or Cu coating. The SiC powder was stirred (using a magnetic stirrer) in a solution, made of 25ml de ionised water and 2.5ml of nitric acid, for 5 minutes. The solution - acidic now, was neutralised by slowly adding an alkali solution, sodium hydroxide (NaOH), with the help of a pipette, to achieve a pH value of approximately 7. The alkali solution used, was prepared by dissolving 2 gm of NaOH in 75ml of de ionised water. A pH meter and litmus papers were used to test the neutralisation of solution. After the solution has been neutralised, it was filtered and dried in the oven as described previously.

7.5.4 Copper coating

Copper was coated over the SiC particles using an electroless plating technique which deposits the metal uniformly onto surface of the particles without the use of an external source of electricity. Electroless deposition is a chemical reduction process which, once initiated, can be autocatalytic. It uses a series of baths, each progressively applying chemical building blocks, used to support the metallic coating on the substrate. Because the process allows a constant metal ion concentration to bathe all parts of the object, it deposits metal evenly along edges, inside holes, and over irregularly shapes. Metal deposit thickness can be achieved in a range of 0.5 μm to 25 μm by applying different conditions (i.e., plating time and temperature) depending upon intended use (Davis, 1998 and Weil, 1997)

The main stages in the process are described below:

- The first stage is to dissolve 1 gram of cupric acetate in 100 ml of de-ionized water in a beaker. A magnetic stirrer was used to mix the solution.
- 3-5 gm of SiC was added to the solution which is then stirred for about 5 minutes to ensure good exposure of SiC surface.
- 6.25 ml of hydrazine hydrate (N_2H_4) was added slowly to the solution using a pipette. A nitrous gas emission was observed upon introduction of hydrazine to the copper acetate solution. As the latter is not compatible with hydrazine, it reacts and copper ions turn into a precipitate, which is deposited onto the silicon carbide powder.
- The resulting solution was then stirred for 30 minutes.
- The reaction product was finally filtered and dried in the oven as before.

Silicon carbide particles were now ready to be mixed with aluminium alloy particles.

7.5.5 Mixing of MMC powder

Generally, mixing of powders serves the following functions:

- separation of interlocked aggregates of particles
- achievement of uniform distribution of reinforcement
- if appropriate, prevention of breakage of high aspect ratio (length/diameter) whiskers

Aluminium and silicon carbide particles are at this stage mixed together in a ratio of 9:1 (as described earlier) to prepare the MMC powder. The blender shown in Fig. 7.4 was used to mix the two powders uniformly for about 10 minutes.

7.5.6 Compaction

Compaction or pressing of powder serves several important functions: the powder particles are consolidated into the desired shape; compacting controls the amount and type of porosity of the finished product; and compacting is largely responsible for the final dimensions of the part, subject to dimensional changes during sintering. Compacting consolidates and densifies the loose powder into a shape called a 'green compact'. With conventional compaction techniques, the compact has the shape and size of the finished product when ejected from the die. It has sufficient strength for in-proce s handling and transfer for sintering.

It is important to note that, before pouring the powder into the mould, the latter required to be cleaned, to make its surface smooth, free of any leftover powder particles from the previous pressing. Compaction involved following sequential steps.

- Mixed powder was poured into the mould using a funnel after a metallic plug has been inserted at the bottom of the mould to constitute the base.
- A metallic punch was inserted on the top of the powders that constitutes the pressing part.
- The whole set was placed under a press, and a pressure of approximately 785 MPa was then applied for a duration of about 2 minutes. This pressure application was sufficient to compress the powder into the required shape.
- Finally, the samples were ejected from the mould with the help of appropriate tooling.

7.5.7 Sintering

Sintering can simply be defined as the process wherein powder particles develop metallurgical bonding and densify under the influence of heat. Densification of the powder depends on the sintering parameters and the alloys involved. Generally, higher sintering temperatures and longer sintering times promote greater densification of sintered parts. Heating and cooling rates and composition of prevailing atmosphere are also important variables. The dimensions of the finished parts are affected by the sintering conditions, as well as by the compacting process and properties of the powder itself (Davis, 1998).

As a general rule sintering is carried out well below the melting point of the metal or the major alloy unless liquid phase sintering is being employed to ensure minimum porosity in high density materials. The final product is generally porous and, in most cases, around 10% porous. Compacts of lower porosity are considered high density materials. While the aim of sintering is to densify porous compacts so as to create mechanical properties approximating to 'normal' alloys, it can be seen that a dense state is not easily achieved. Sintering is thus pore elimination.

Compaction creates the required shape and density. Sintering is then carried out to improve or create the required mechanical, physical or chemical properties. In this process, changes in weight and dimensions of the compact occur, which must be controlled. Weight loss is usually due to loss of volatilises.

Samples in the present work were sintered in vacuum environment at 600C for a duration of 20 minutes, besides the 30 minutes and 160 minutes for heating up and cooling down phases, respectively.

7.5.8 Grinding

The two faces of the samples were ground (on hand grinder) to prepare the surfaces for corrosion tests.

7.6 CORROSION TESTING OF THE MMCs

A series of corrosion tests were carried out at Otto-Von Guericke University, Germany, to evaluate the corrosion performance of the MMCs. Tests carried out included electrochemical, slat spray and immersion test.

Samples Tested

The samples tested were cylindrical in shape with a diameter of 11 mm and of height equal to 5 mm. Reinforcement samples were prepared in a range of Cu coating layers so as to judge the corrosive behaviour of Cu in the material. SiC particles were used in following conditions.

- Uncoated SiC
- Single Cu coated SiC
- Double coated SiC
- Triple Cu coated SiC
- 1 hour Cu bath coated SiC

7.6.1 Electrochemical test

Since corrosion is an electrochemical process, it is possible to evaluate the overall reaction by the use of an external electrical circuit called a potentiostat. When corrosion occurs, a potential difference exists between the metal and its ions in solution. This can be used to monitor changes in current (corrosion) as now discussed. Oxidation is a reaction with a loss of electrons (anodic the reacting electrode is the anode); reduction is a reaction with a gain of electrons (cathodic the reacting electrode is the cathode). Rather than allowing electrons released from the corrosion reaction to combine with hydrogen ions, by internal circuitry, these electrons can be removed, sent through a potentiostat, then causing a cathodic (or anodic) reaction to occur at a platinum counter electrode.

The potentiostat has a three electrode system: a reference electrode (generally a saturated calomel electrode (SCE)), a platinum counter, or auxiliary, electrode through which current flows to complete the circuit, and a working electrode.

The potentioastat (Fig 7.5) allows control of the potential, either holding it constant at a given potential, stepping from potential to potential, or changing the potential anodically or cathodically at some linear rate.

In the study of anodic cathodic polarisation behaviour of a metal/environment system, the potentiostate provides a plot of the relationship of current changes resulting from changes in potential and is most often presented as a plot of log current density versus potential, or Evans diagram.

Test Conditions I

Solution 0.1 N NaCl

Potential 0.5 mV s

Temperature 25C

Results

The first part of the test consisted of two testing cycles on each sample, maintaining the maximum limit of current density equal to 10 A m^2. Samples were ground every time before the test in order to expose the fresh surface. Potential-current density curves, representing the corrosion tendency of samples were obtained after each cycle in the test, as shown in Fig. 7.6.

Curves generated by all the samples during their both cycles of testing were similar. All the curves exist in a close range (-620 to 580 mV_{SCE}) and show that corrosion rates are similar on all the samples.

Samples were also viewed under a high power optical microscope but no difference could be observed amongst the tested samples.

Test Conditions II

In the second part of the test, the solution concentration was intensified as given below.

Solution 1 N NaCl

Potential 0.5 mV s

Temperature 25C

Results

Potential current density curves generated are shown in Fig. 7.7. This time, each sample was tested once. Again, all the curves lie in a close region (-710 to 660 mV_{SCE}). Uncoated sample has a slightly earlier rise of curve (blue) This difference is however not any significant and on repeated cycles of testing all curves showed similar profiles, as in Fig. 7.6.

Results of this test show that there was not any difference in the corrosion performance of the samples and that Cu coatings therefore, add no corrosive impacts onto the material.

7.6.2 Salt spray test

The samples were tested under salt spray exposure to check the consistency of results obtained from the electrochemical test. Details of the salt spray test have previously been discussed in chapter 3; the procedure and conditions adopted were the same as described in section 3.4.2.

After 96 hours of salt spray exposure, samples were observed under low and high power optical microscopes. It was observed that all samples exhibited pitting corrosion attack on the surface as shown in Figs. 7.8, 7.9, 7.10, 7.11 & 7.12. There were no notable differences observed between the corrosion attack on different samples; instead it revealed that all the samples exhibited similar behaviour irrespective of Cu coatings applied to SiC reinforcement.

7.6.3 Immersion test

An immersion test was also conducted to further study the corrosion behaviour of the samples. Immersion test details have already been described in 3.4.1.

Samples were observed under various magnifications of optical microscopes. There was pitting corrosion observed on all samples similar to slat spray test. It appeared that pitting corrosion attacked all the samples equally since the distribution and size of the pits were not distinguishable amongst different samples.

The images of the test samples do not indicate any difference in the corrosion behaviour of different samples under the tested conditions indicating that Cu coating did not play a role in the corrosion behaviour of the samples.

7.7 CONCLUSIONS

- An electrochemical test provides precise information on the corrosion behaviour of materials. Repeated electrochemical tests have shown no notable difference in corrosion performance amongst the tested samples, indicating that Cu coating (s) of SiC reinforcement into an Al 6061 matrix does not decrease the corrosion resistance of the MMC.

- Salt spray and immersion tests also revealed no difference in corrosion performance of samples containing Cu coated and uncoated SiC reinforcement. Results of the three tests therefore, validate the argument that Cu coating, of the type described in this thesis, does not bring any additional corrosion loads onto this particular MMC.

- SiC reinforcement used is 10 o by mass in the investigated MMC. Cu coating on SiC particles makes up a proportion in the MMC that might be small enough to alter its corrosion performance.

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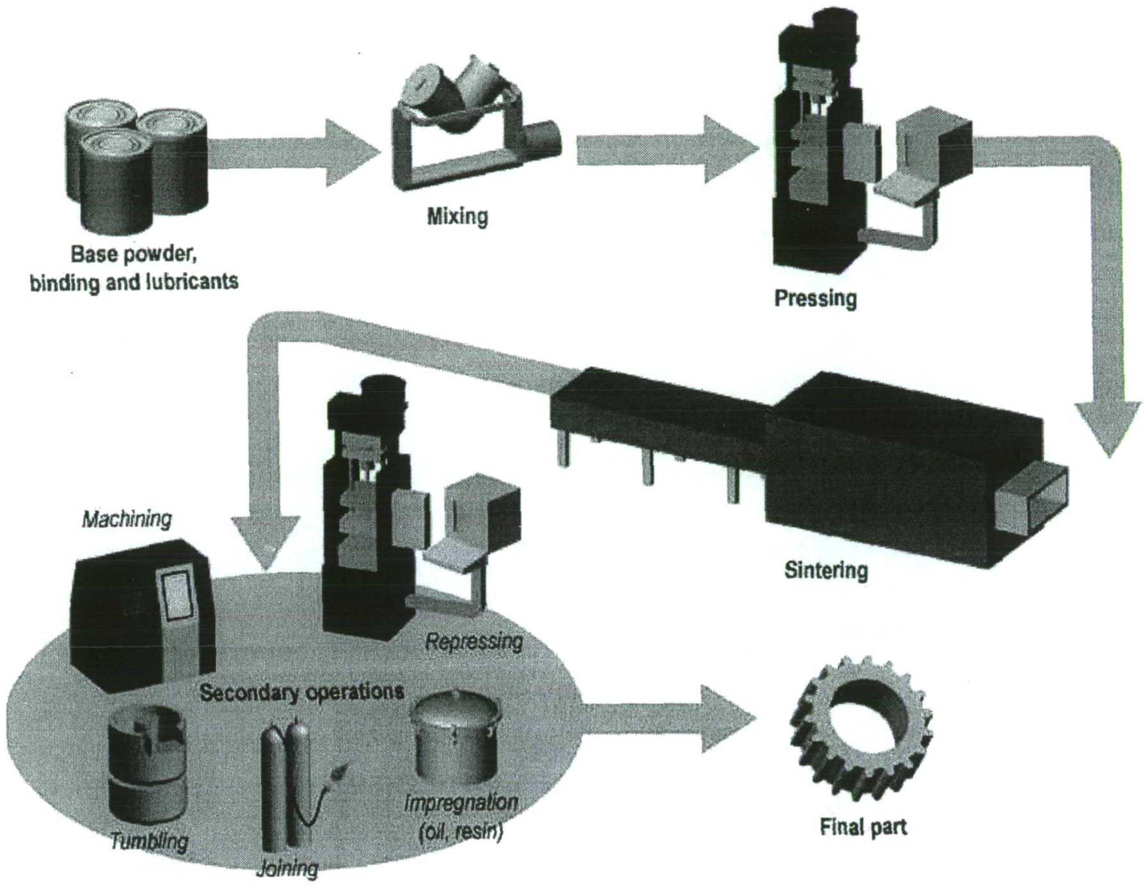

Fig.7.1 Steps involved in P/M process
(http://www.precitech.ca/pmproc.htm#etape1)

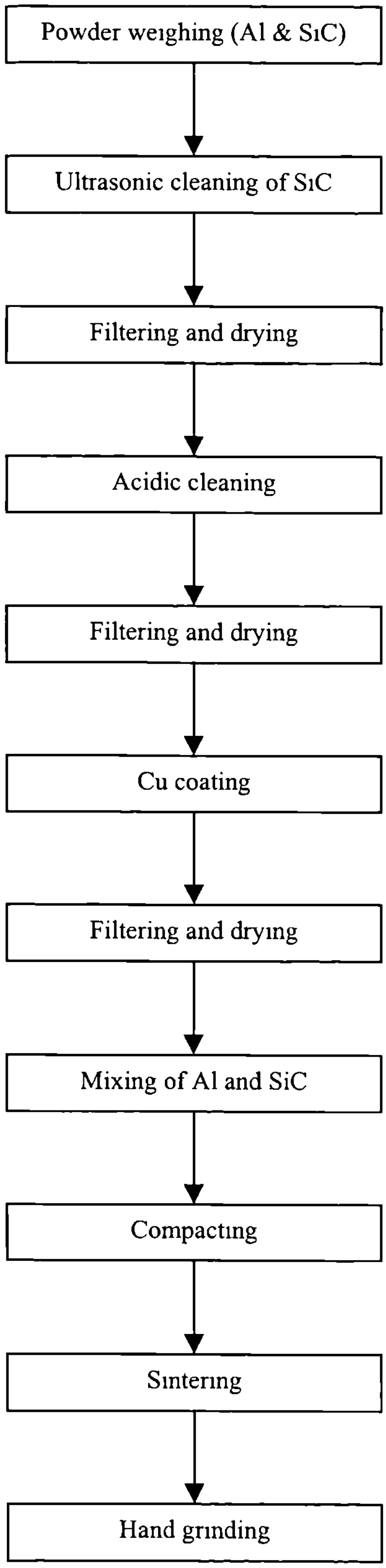

Fig. 7.2 Sequential steps involved in preparation of the samples

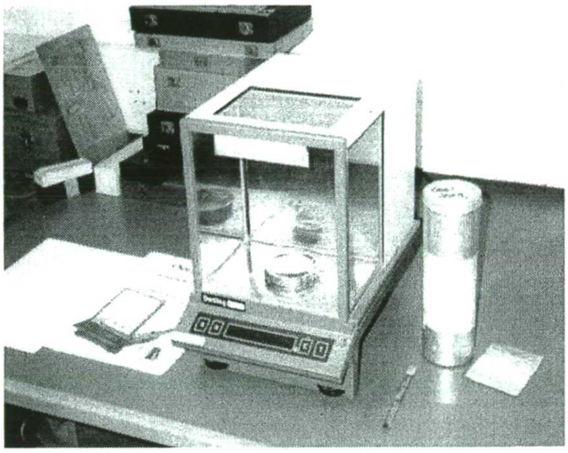

Fig. 7.3 Digital balance

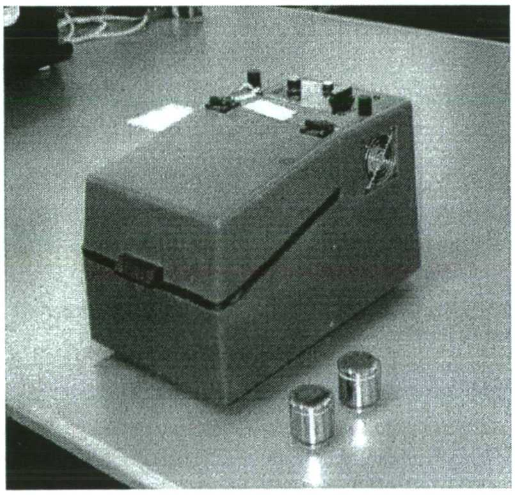

Fig. 7.4 Blender with the two containers

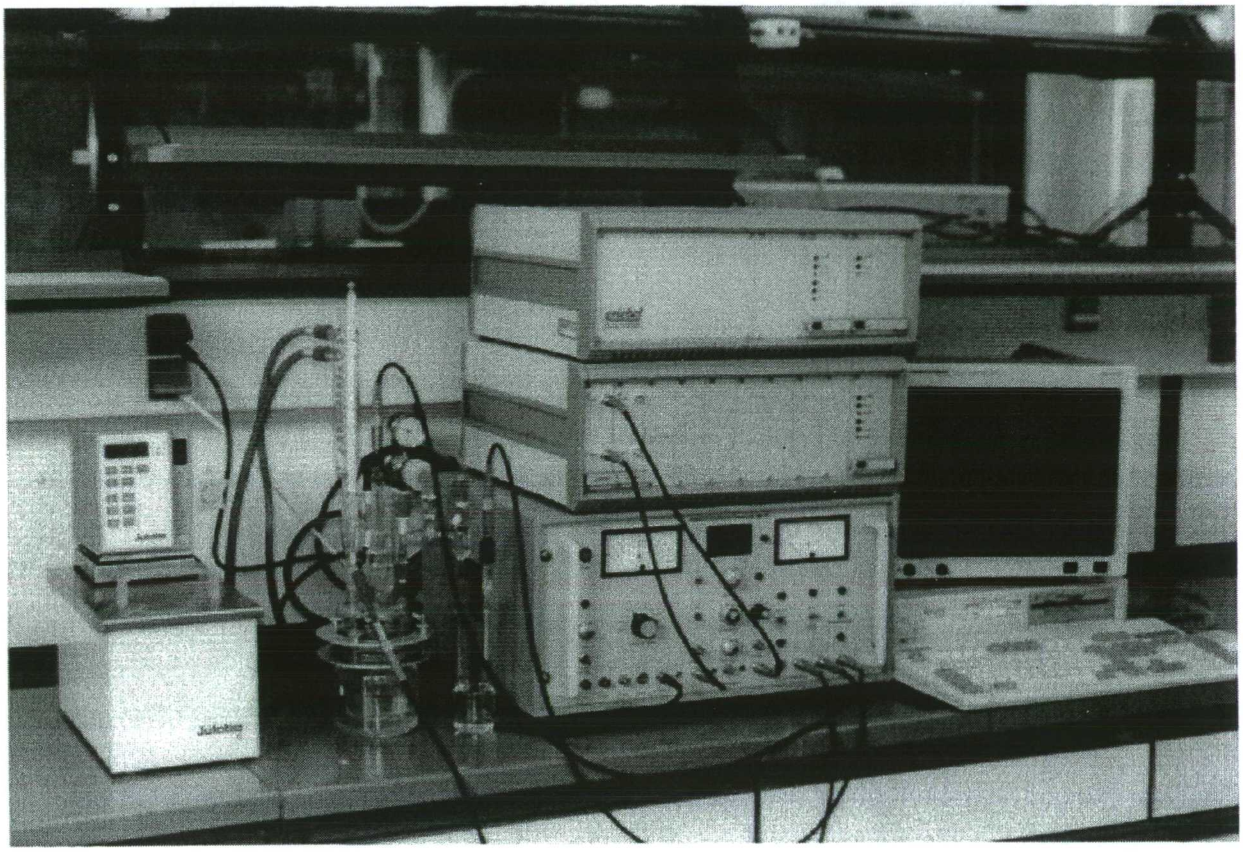

Fig. 7.5 Electrochemical testing equipment

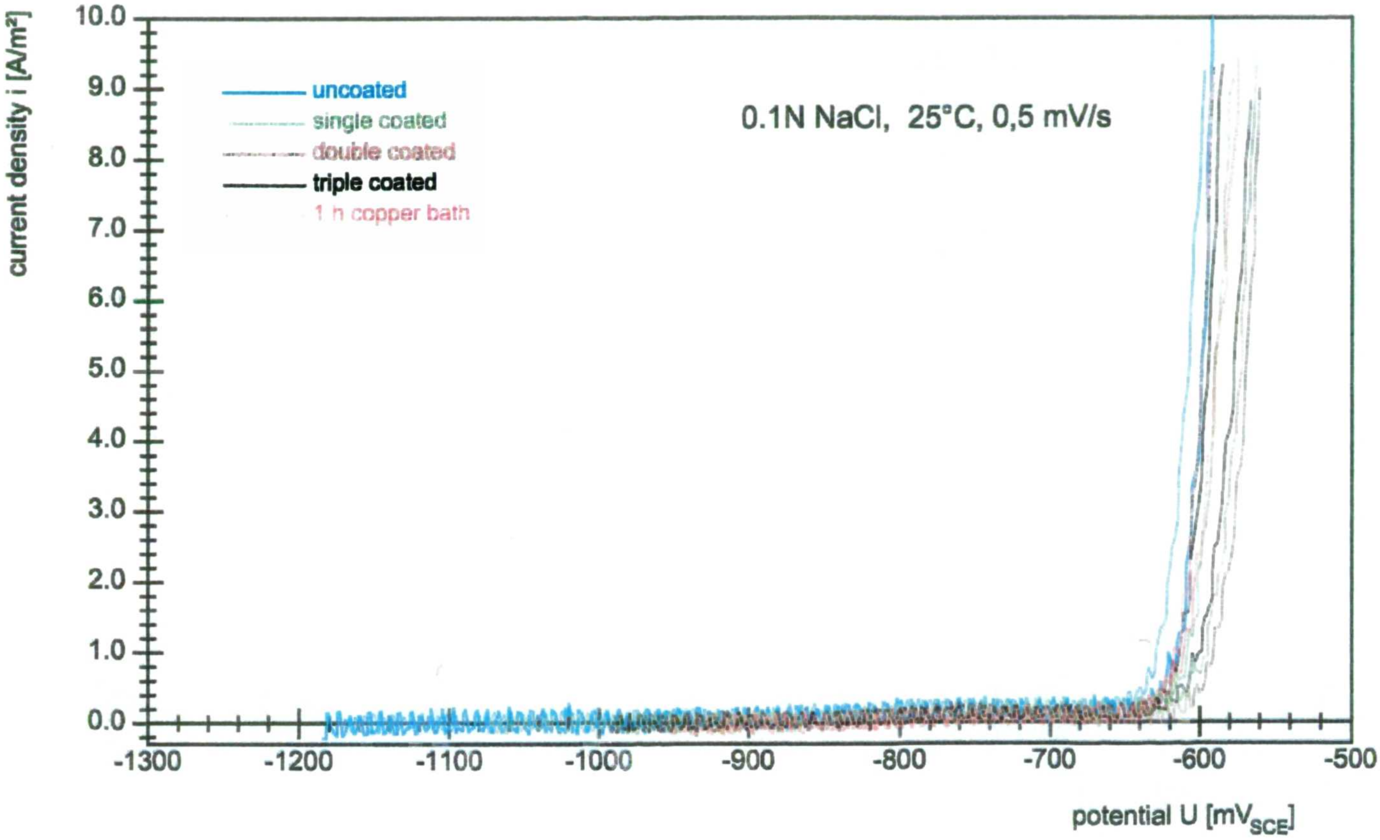

Fig. 7.6 Curves generated are in a close range which indicate that corrosion rates are similar in all the samples (Original is in colour)

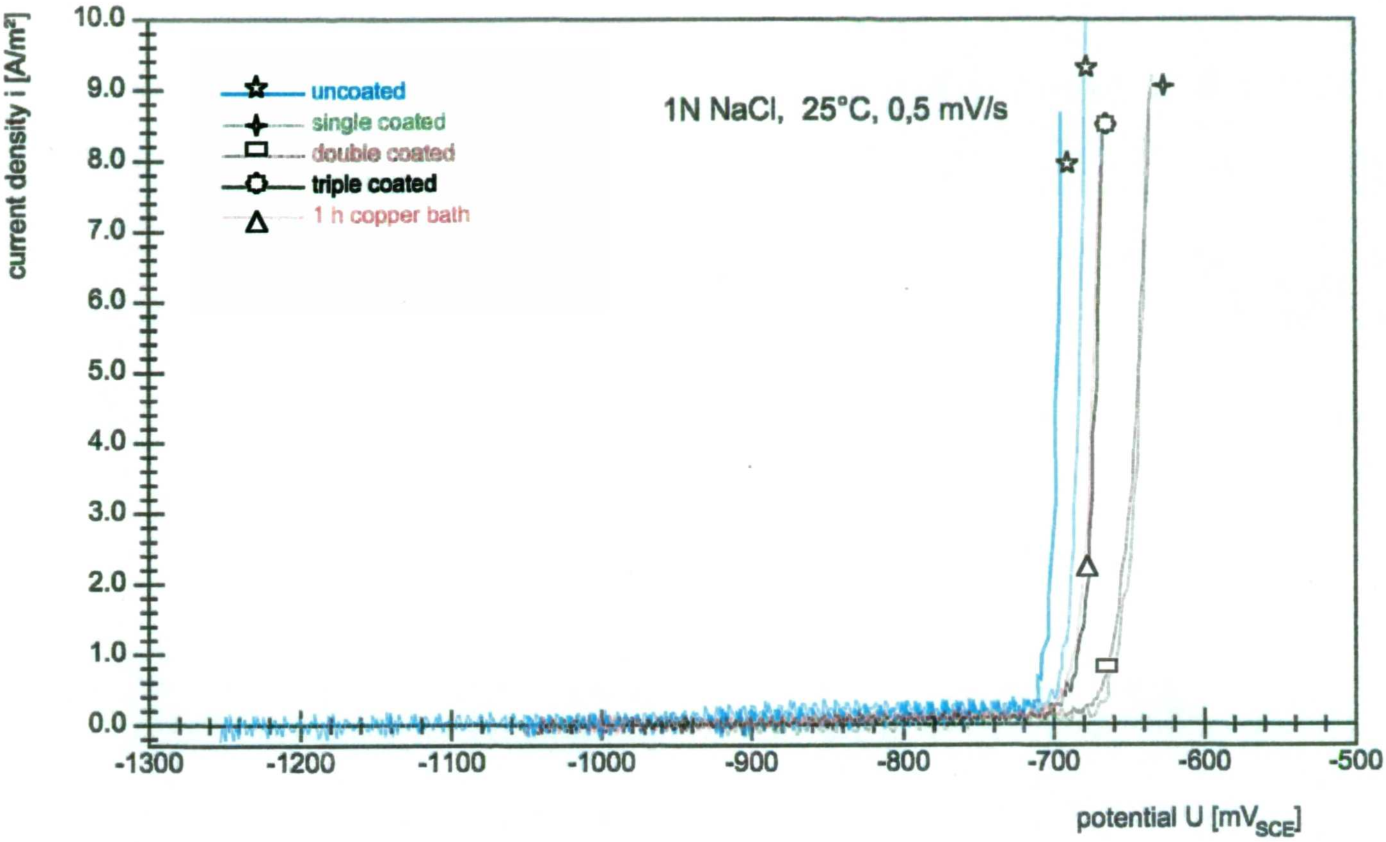

Fig. 7.7 Closely located curves indicate that corrosion rate is similar in all samples

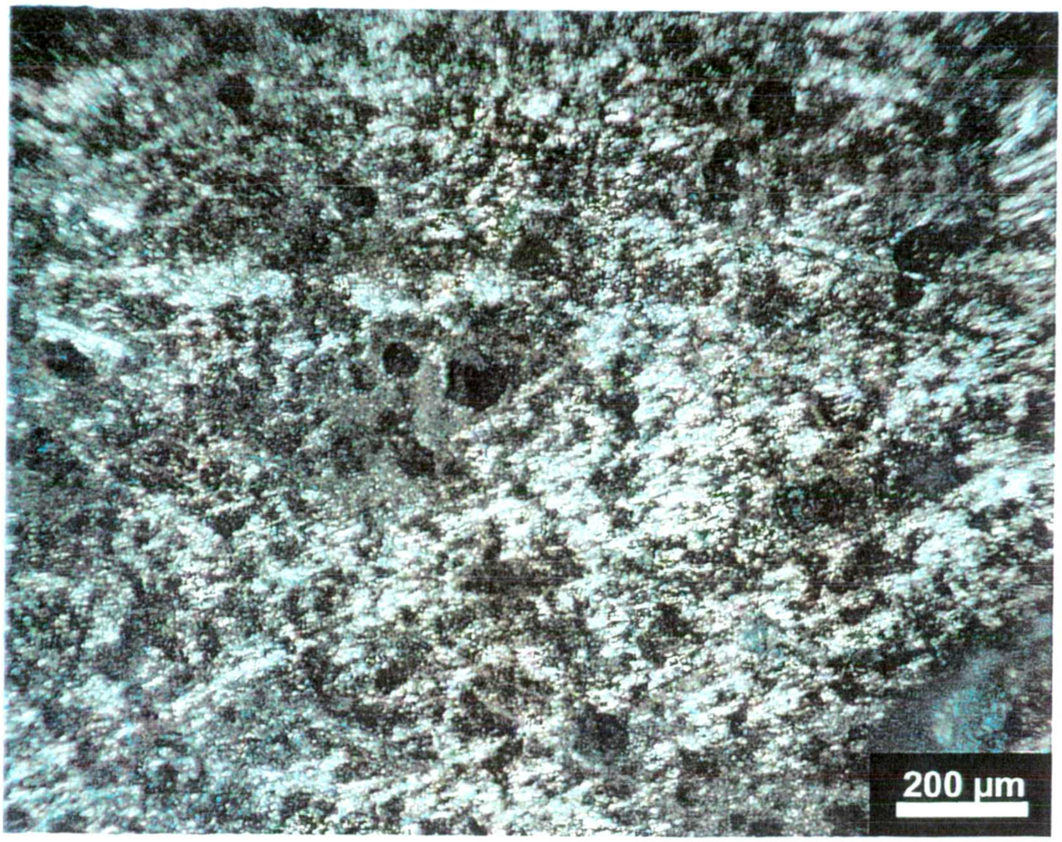

Fig. 7.10 Double Cu coated SiC based MMC showing pitting corrosion after the salt spray test @ magnification of 100

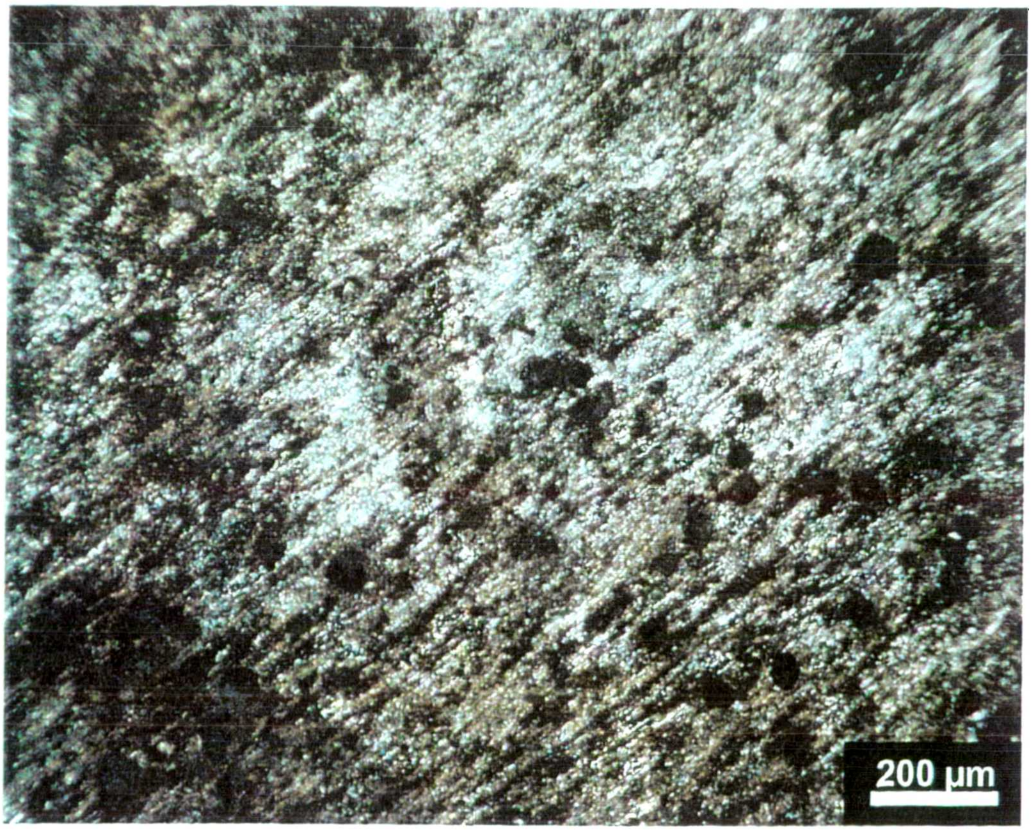

Fig. 7.11 Triple Cu coated SiC based MMC showing pitting corrosion after the salt spray test @ magnification of 100

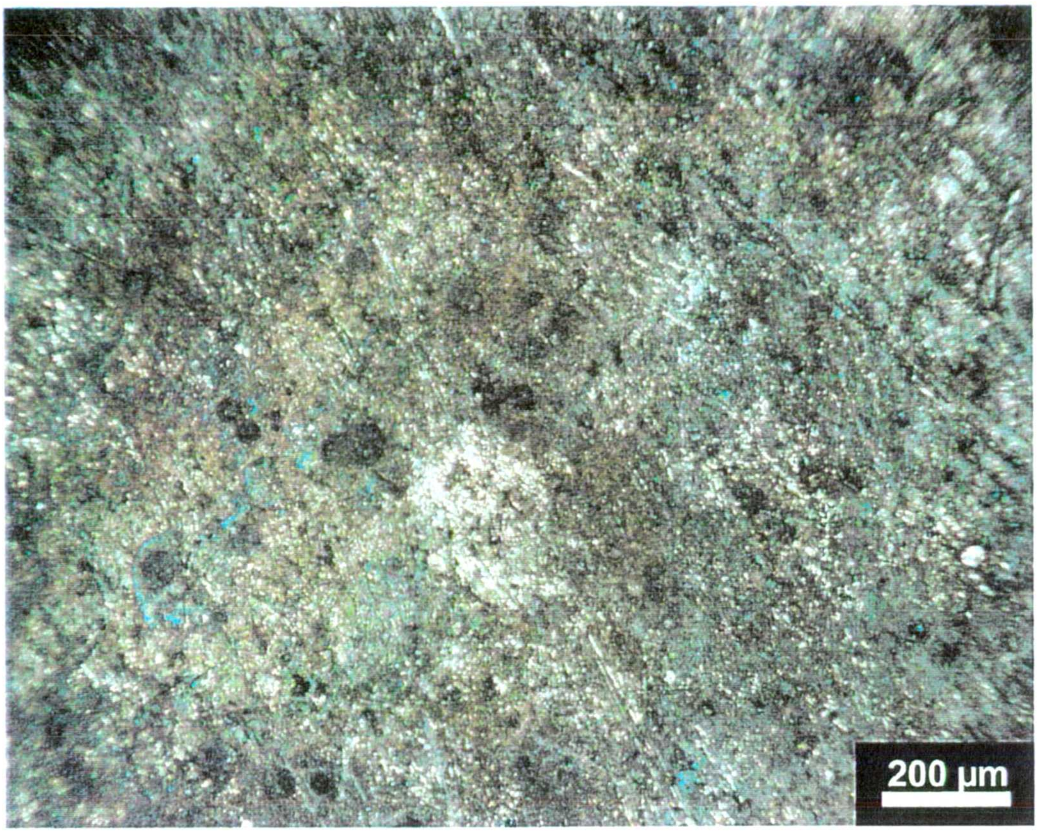

Fig.7.8 Uncoated SiC based MMC showing pitting corrosion after the salt spray test @ magnification of 100

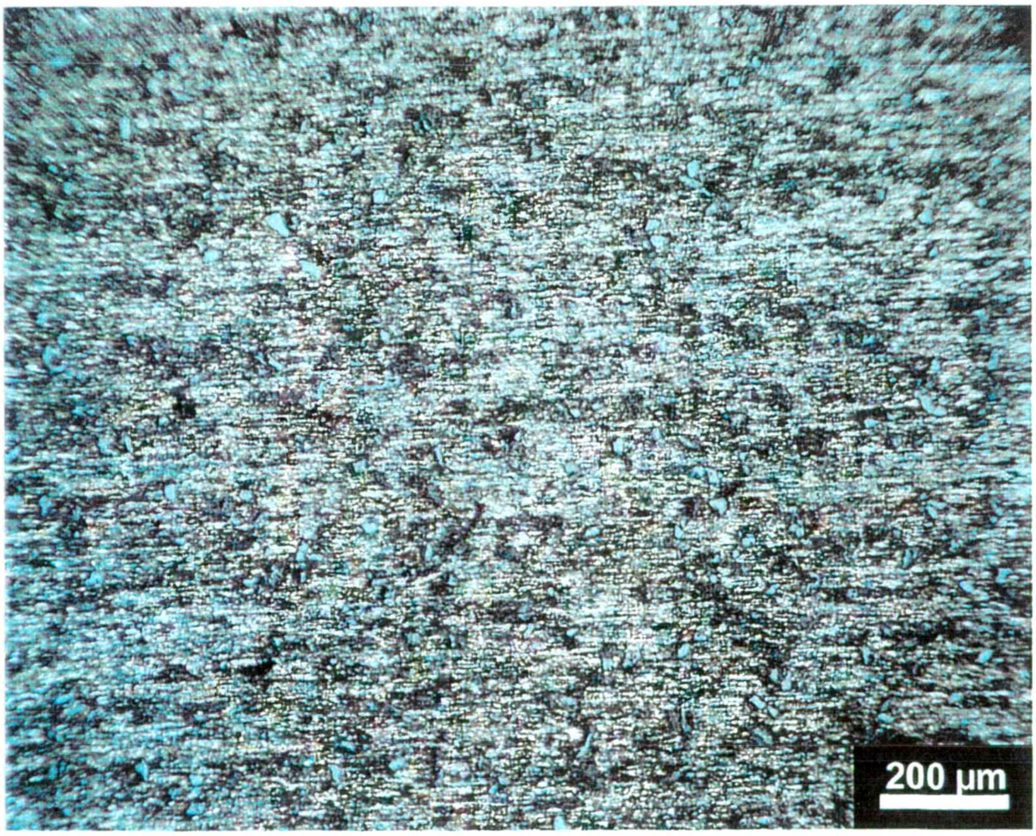

Fig.7.9 Single Cu coated SiC based MMC showing pitting corrosion after the salt spray test @ magnification of 100

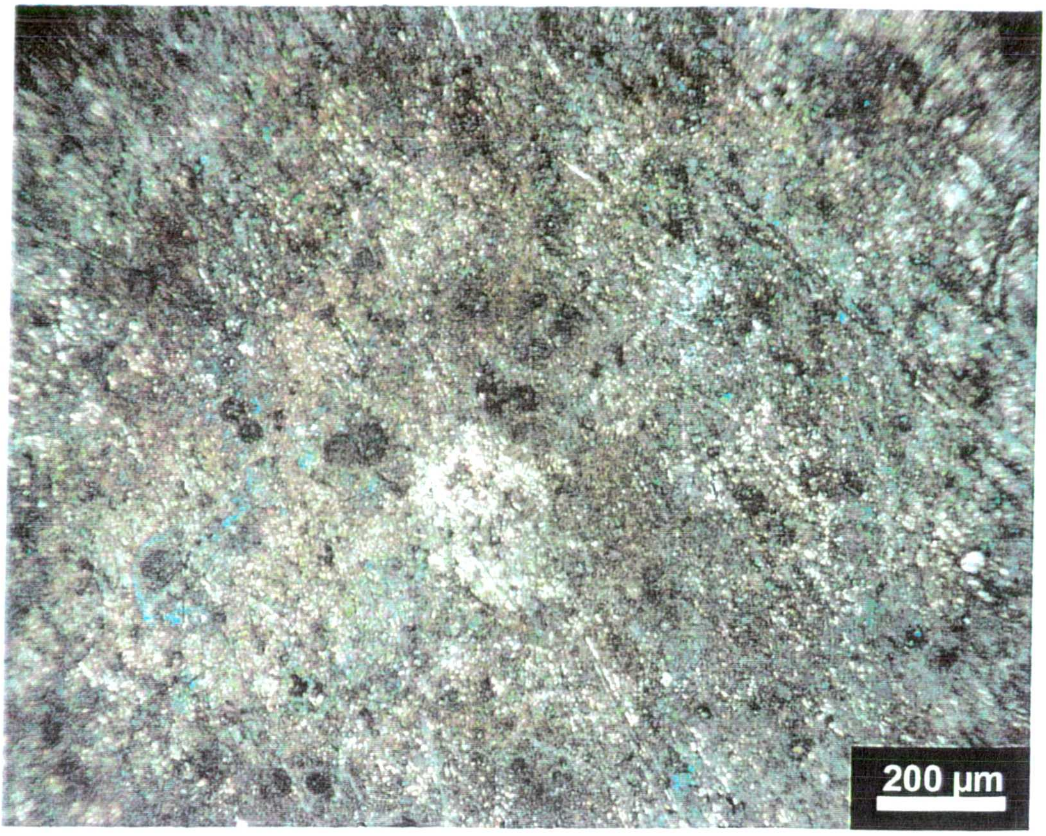

Fig. 7.12 1 hour Cu coated SiC based MMC showing pitting corrosion after the salt spray test @ magnification of 100

8 CONCLUSIONS

One of the prime objectives of this research project was to carry out life cycle assessment of aluminium clad timber windows. A detailed energy and environmental impact assessment of aluminium clad timber windows has been carried out. Weathering performance of candidate windows has been highlighted and the accelerated tests have provided valuable information in this regard. Durability and service life issues of windows have been addressed. Cost effectiveness and productivity of aluminium clad timber windows have been investigated on the basis of life cycle cost analysis (LCCA) methodology while value engineering (VE) of aluminium clad timber windows has also been addressed By carrying out a comprehensive comparison the merits and demerits of aluminium, aluminium clad timber, PVC and timber windows have been undertaken. Useful information regarding corrosion characteristics of Al-SiC (Cu coated) MMC has been obtained through accelerated corrosion testing.

The findings of the present work are summarised in the following sections.

8.1 WEATHERING OF WINDOW MATERIALS

Weathering is the deterioration of materials with the passage of time due to their exposure to the environment and is a naturally occurring process. Natural atmospheric factors, especially solar energy in the form of ultra-violet (UV) radiation and moisture are the main elements that initiate the degradation mechanism. These are accompanied by other degradation factors such as oxygen, temperature, wind and pollutants. However, the rate of degradation of different materials differ even under similar conditions depending upon their sensitivity towards particular weathering elements.

Corrosion, an electrochemical process by nature, is the general mode of deterioration in metals such as aluminium, caused by environmental impacts. Although aluminium has good corrosion resistance characteristics, however, it still can get corroded under intensive corrosive conditions. Surface treatment on aluminium can further improve its resistance against corrosion. Degradation of timber is characterised as both biological (by insects and fungi) and non-biological (weathering) factors. Weathering is caused by the photo-oxidation process under the influence of UV rad ation, moisture and wind abrasion, resulting in a change of surface colour due to decomposition of the lignin the chemical constituent of cellular tissues that has the hardening and bonding function in the cell walls . Timber can be protected from weathering impacts by applying preservatives and surface finishes. Weathering performance of PVC d pends upon its composition and formulation, however, in general, PVC is sensitive to UV rad ation which affects the chemical bonding of the material. PVC undergoes a dehydrochlorination process which is characterised by the formation of polyene (a conjugated double bond sequence), due to evolution of hydrogen chloride (HCl). Polyene absorbs the visible light causing the polymer to become discoloured. Weathering properties of PVC can be improved by the addition of certain stabilisers.

8.2 ACCELERATED TESTING

The results of accelerated tests have confirmed the expected performance of different window frame materials subjected to environmental impacts. These results are summarised below.

- Humidity has been found to be affecting only the uncoated aluminium frames in the form of corrosive attacks. Timber and PVC frames in general have not shown any sensitivity towards humidity. High temperature/heat has been a factor that considerably affects the PVC profiles in the form of discoloration. Unpainted timber received only a minor colour fading. Painted timber windows have shown resistance against humidity and temperature. Surface coatings have been found to increase the resistance of both timber and aluminium against applied environmental conditions. Aluminium clad timber windows remained unaffected both by humidity and temperature.

- UV test results indicate that PVC windows are more likely to be affected by UV radiation than other window designs. The test results have indicated the sensitivity of PVC towards high temperature and UV exposures which cause molecular breakdown in the material resulting into discoloration and loss of aesthetic appearance. Unpainted timber windows receive minor impacts, while paint on the timber frames further reduces these impacts. Aluminium and aluminium clad timber windows are unaffected by UV.

- Immersion test that was only carried out for the aluminium windows has revealed the importance of surface treatments. The corrosive solution in the immersion test caused pitting corrosion on the surface of uncoated aluminium samples, while anodised and powder coated samples remained resistant against the corrosive solution.

- Aluminium clad timber windows in general remained resistant against all the weathering conditions in the tests. They also have appeared to possess overall better weathering performance as compared to aluminium, PVC and timber windows. Cladding acts like a shield protecting the underneath timber from severe impacts such as UV, and flux of wind and rain. With the help of proper surface treatment, e.g. anodising or powder coating, aluminium exhibits good corrosion resistance.

- The weathering conditions in accelerated test chambers are artificially produced which are normally too aggressive than in a natural environment, to a celerate the degradation process, in order to obtain results in a shorter time. This typical nature of conditions sometimes generates excessive stresses on tested materials, for example, the corrosion of aluminium samples and a total discoloration of PVC. The important factor with accelerated testing is that it should rightly identify the nature of problem that a material might experience due to environmental conditions, the intensity of problem however may deviate in real life. It is therefore, necessary to strike a balance between the severity of accelerated conditions (and consequent d gradation produced) and the real life situation, when interpreting the results.

8.3 ECOLOGY OF ALUMINIUM-CLAD TIMBER WINDOWS

The basic ingredients of an aluminium-clad timber window are; timber, aluminium, glass and inert gas, with other materials such as rubber, plastic, zinc and steel used in small proportions. All of the four basic materials owe certain levels of environmental loads in their transformation route into a finished window. Aluminium and glass have a high global warming potential (GWP) due to their energy extensive production processes and the resulting pollutants. Argon, as the infill gas does not generate any notable environmental load. Krypton and Xenon however, cause quite a significant amount of environmental burden during their production. Timber in windows, inflicts only a small quantity of environmental load. It is also worth mentioning that timber is regarded as a renewable material due to its well organised replacement cultivation which is itself an environmentally friendly process. Also, aluminium's ability to be recycled is its appealing quality and helps in lessening the severe environmental impacts associated with its primary production.

Embodied energy assessment has shown that the energy content of a standard double glazed aluminium clad window is 899 MJ, 1402 MJ, and 5.4 GJ for Argon, Krypton and Xenon infill gases, respectively. Energy consumed in powder coating has been estimated as 27 MJ and the total embodied energy of adding aluminium cladding to the window has been evaluated as 243.4 MJ.

In simple double glazed windows, aluminium strips are used as a boundary shield around glazing. When cladding is applied there is no more a need of this outer protection. Therefore in cladding a window, the extra amount of aluminium used is in fact 2.46 kg, that contains embodied energy of 134.6 MJ. Considering the powder coating energy consumption of 27 MJ, the extra energy associated with cladding is 161.6 MJ. The aluminium cladding brings an additional 21 %, 13 % and 3 % of embodied energy respectively for Argon, Krypton and Xenon filled double glazed windows.

8.4 LIFE CYCLE COST ANALYSIS & VALUE ENGINEERING

Major cost factors involved in life cycle costing of aluminium clad timber and timber windows are; capital cost, energy (heat loss) cost - electricity or gas, planned maintenance cost - painting or staining and cleaning cost in case of commercial use.

Capital cost of windows is not only driven by the type of frame but also by the composition of glazing unit. Aluminium clad timber windows are almost 14-18% more expensive than timber widows for the same glazing unit Glazing cost varies with the number of glass panes, infill gas and low e coating.

Energy cost, in the form of heat loss through the window, is a major part of the life cycle cost of the window. Energy cost becomes particularly significant in harsher weather conditions. It can however be significantly reduced by selecting well insulated glazing units, that employ modern technologies such as multiple glazing, inert infill gases and low-e coatings. It has been found that heat loss can be reduced by an amount of almost 60% by using low emissivity coated triple glazed unit with Argon infill gas. Figures show that at an Aberdeen location, for a double glazed air filled window the annual heat loss is 275 kWh while for a triple glazed Argon filled window with low emissivity coatings this heat loss is reduced to 112 kWh. This 60% reduction in heat loss reduces the energy cost in same proportion. Energy cost is much lower when gas is used as the heating medium. Analysis shows that for simple double glazed windows in cold locations like Aberdeen LCC of windows can be reduced by 36% just by using gas as the heating source instead of electricity.

It has been seen that maintenance cost becomes the vital factor in life cycle costing; despite the higher capital cost, aluminium clad timber windows are cheaper than timber windows over a 40-year life-span. This is due to the lesser maintenance required for aluminium clad timber windows. Analysis has shown that over 40 years, painting and staining costs of a timber window are £90 and £180, respectively. On the other hand, for the same period of time, painting and staining costs of an aluminium-clad timber window are £14 and £33, respectively. It has been found that in terms of capital cost an aluminium clad timber window is more expensive than a timber window by an amount of £28, however, over 40-year service life, the aluminium clad timber window is £48-£118 cheaper than the timber window due to less maintenance cost.

Analysis has shown that the cleaning cost is the most significant factor in life cycle costing windows. For example, at an Edinburgh location, cleaning cost of a window can be more than 60% of whole life cost of a window. Elimination of cleaning factor in domestic sector can significantly cut down the life cycle cost of windows

8.5 COMPARISON OF DIFFERENT WINDOWS

The comparative assessment of four different windows, i.e., aluminium, aluminium clad timber, PVC and timber, have generated the following results.

- It has been found that aluminium windows have the highest level of embodied energy as compared to other windows. Timber windows have been estimated to be possessing the lowest embodied energy. Comparison based on a krypton-filling shows that aluminium clad timber, PVC and aluminium windows, respectively, possess 1.13, 3.6 and 8.1 times more embodied energy than a timber window.

- Aluminium windows have the highest level of affiliated environmental loads mainly due to large amount of energy consumption during aluminium's production process and resulting pollutants.

PVC also exhibit large amounts of environmental loads throughout its life; production, use, and most importantly disposal phase Timber windows are least harmful as they add only minor environmental loads. Aluminium clad timber windows, in this regard, largely possess the characteristics of timber with additional loads of aluminium cladding. Aluminium windows are the only completely recyclable windows. Their recyclability helps bringing down the associated energy and environmental loads. Quantitative assessment of impacts resulting from disposal of PVC and timber windows is not available, it is however evident that PVC windows due to their complex compositions of PVC materials, are not normally recycled. Rather they are land-filled or incinerated with a consequence of large amounts of toxicity generated. Timber windows can be land-filled, incinerated or downcycled.

- Durability and service life of windows largely depend upon the quality of materials employed, exposed conditions and the degree of care taken. Service life investigation based on presently undertaken survey has indicated that aluminium clad timber windows have the longest service life. Survey results provided an estimation of service life span of windows, that is, 46.7, 43.6, 39.6, 24.1 years for aluminium clad timber, aluminium, timber and PVC windows, respectively.

- All windows require maintenance to keep them functioning properly. Aluminium, PVC and aluminium clad timber windows require to be cleaned regularly to maintain their aesthetic appearance. Timber windows require to be painted or stained periodically to keep them protected from weathering impacts.

- Price comparison of windows is quite an involved process due to a number of factors such as the quality of product and marketing tools such as, discounts and incentives. However the general perception is that aluminium windows are more expensive than the rest of candidate windows. PVC and timber windows are within close proximity to each other, while aluminium clad timber windows are about 14-18 % more expensive than timber windows of exactly the same type.

- It has been reported that window market follows a geographical trend; in central Europe PVC windows dominate the market, in Scandinavia timber while in southern Europe aluminium windows are the preferred choice.

8.6 CORROSION TESTING OF Al-SiC MMCs

Electrochemical test provides precise information on corrosion behaviour of materials. Repeated electrochemical tests have not shown any notable difference in corrosion performance amongst the tested samples, which indicate that Cu coating of SiC reinforcement into Al 6061 matrix does not decrease the corrosion resistance of the MMC Salt spray and immersion tests also have revealed no difference in corrosion performance of samples containing Cu coated and uncoated SiC reinforcement.

8.6 CORROSION TESTING OF Al SiC MMCs

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8.7 RECOMMENDATIONS FOR FUTURE WORK

- It is recommended, as part of future work, to expose different types of windows in outdoor environments to study their comparative weathering performance under natural conditions. Data collected should be used to validate the results obtained from accelerated ageing tests.

- Environmental impacts of landfill disposal of timber and PVC windows can be a prospective issue for research particularly in life cycle assessment of PVC windows, this investigation can be of great interest.

- Pollution caused by applied surface coatings, e.g. paints and stains, can also be addressed to consolidate the existing LCA studies of windows.

- Economics of the routine maintenance and disposal costs of windows can also be investigated as part of their life cycle costing. Disposal cost may be removal of windows, scrapping or selling them, adjusted for any tax allowance or charge at the point of sale.

APPENDIX A

Table A1 Life cycle costing of aluminium clad timber and timber windows at an Aberdeen location with 6 different glazing compositions with four different running options gas paint, gas stain, electricity paint and electricity stain domestic applications

Timber windows

	4-16Air-4	4-16Air-e4	4-16Ar-e4	4-10Kr-e4	e4-16Air-4-16Air-e4	e4-16Ar-4-16Ar-e4
U-Value (W m^2 K)	3 6	2.1	2.0	1.7	1.6	1 5
Costs (£)						
Capital	143	154	173	209	162	193
Electricity	1140	656	624	531	499	468
Gas	329	189	180	153	144	135
Painting	90	90	90	90	90	90
Staining	180	180	180	180	180	180
Totals						
Electricity Paint	1373	900	887	830	751	752
Electricity/Stain	1463	990	977	920	841	842
Gas/Paint	561	434	443	452	396	418
Gas/Stain	651	524	533	542	486	508

Al-clad Timber windows

	4-16Air-4	4-16Air-e4	4-16Ar-e4	4-10Kr-e4	e4-16Air-4-16Air-e4	e4-16Ar-4-16Ar-e4
Capital	171	183	201	237	190	221
Electricity	1140	656	624	531	499	468
Gas	329	189	180	153	144	135
Painting	14	14	14	14	14	14
Staining	33	33	33	33	33	33
Totals						
Electricity/Paint	1325	853	840	782	703	704
Electricity/Stain	1344	872	859	801	722	723
Gas Paint	513	386	395	404	348	370
Gas Stain	533	405	414	423	367	389

Table A2 Life cycle costing of aluminium clad timber and timber windows at an Edinburgh location with 6 different glazing compositions with four different running options gas paint, gas stain, electricity paint and electricity/stain - domestic applications

Timber windows						
	4-16Air-4	4-16Air-e4	4-16Ar-e4	4-10Kr-e4	e4-16Air-4Air-e4	e4-16Ar-4-16Ar-e4
U-Value (W m^2-K)	3.6	2.1	2.0	1.7	1.6	1.5
Costs (£)						
Capital	143	154	173	209	162	193
Electricity	1043	599	571	485	457	428
Gas	301	173	165	140	133	124
Painting	90	90	90	90	90	90
Staining	180	180	180	180	180	180
Totals						
Electricity/Paint	1275	844	834	784	709	712
Electricity/Stain	1365	934	924	874	799	802
Gas/Paint	533	418	428	439	385	407
Gas Stain	623	508	518	529	475	497

Al-clad Timber windows						
	4-16Air-4	4-16Air-e4	4-16Ar-e4	4-10Kr-e4	e4-16Air-4-16Air-e4	e4-16Ar-4-16Ar-e4
Capital	171	183	201	237	190	221
Electricity	1043	599	571	485	457	428
Gas	301	173	165	140	133	124
Painting	14	14	14	14	14	14
Staining	33	33	33	33	33	33
Totals						
Electricity/Paint	1228	796	786	736	661	664
Electricity/Stain	1247	815	805	755	680	683
Gas/Paint	486	370	380	391	337	359
Gas/Stain	505	389	399	411	356	378

Table A3 Life cycle costing of aluminium clad timber and timber windows at a Manchester location with 6 different glazing compositions with four different running options gas paint, gas stain, electricity paint and electricity stain - domestic applications

Timber windows

	4-16Air-4	4-16Air-e4	4-16Ar-e4	4-10Kr-e4	e4-16Air-4Air-e4	e4-16Ar-4-16Ar-e4
U-Value (W m^2-K)	3.6	2.1	2.0	1.7	1.6	1.5
Costs (£)						
Capital	143	154	173	209	162	193
Electricity	938	539	513	437	414	385
Gas	271	155	148	126	119	112
Painting	90	90	90	90	90	90
Staining	180	180	180	180	180	180
Totals						
Electricity Paint	1171	783	776	735	666	669
Electricity/Stain	1261	873	866	825	756	759
Gas/Paint	504	400	411	425	371	395
Gas/Stain	594	490	501	515	461	485

Al-clad Timber windows

	4-16Air-4	4-16Air-e4	4-16Ar-e4	4-10Kr-e4	e4-16Air-4-16Air-e4	e4-16Ar-4-16Ar-e4
Capital	171	183	201	237	190	221
Electricity	938	539	513	437	414	385
Gas	271	155	148	126	119	112
Painting	14	14	14	14	14	14
Staining	33	33	33	33	33	33
Totals						
Electricity/Paint	1123	736	729	688	618	621
Electricity/Stain	1142	755	748	707	637	640
Gas Paint	456	352	363	377	323	347
Gas Stain	475	371	382	396	342	366

Table A4 Life cycle costing of aluminium clad timber and timber windows at a Wales location with 6 different glazing compositions with four different running options gas paint, gas stain, electricity paint and electricity stain - domestic applications

Timber windows						
	4-16Air-4	4-16Air-e4	4-16Ar-e4	4-10Kr-e4	e4-16Air-4Air-e4	e4-16Ar-4-16Ar-e4
U-Value (W m^2-K)	3.6	2.1	2.0	1.7	1.6	1.5
Costs (£)						
Capital	143	154	173	209	162	193
Electricity	873	513	489	416	391	367
Gas	258	149	142	121	113	106
Painting	90	90	90	90	90	90
Staining	180	180	180	180	180	180
Totals						
Electricity/Paint	1106	758	752	715	643	650
Electricity/Stain	1196	848	842	805	733	740
Gas Paint	491	393	405	419	365	389
Gas Stain	581	483	495	509	455	479

Al-clad Timber windows						
	4-16Air-4	4-16Air-e4	4-16Ar-e4	4-10Kr-e4	e4-16Air-4-16Air-e4	e4-16Ar-4-16Ar-e4
Capital	171	183	201	237	190	221
Electricity	873	513	489	416	391	367
Gas	258	149	142	121	113	106
Painting	14	14	14	14	14	14
Staining	33	33	33	33	33	33
Totals						
Electricity Paint	1058	710	705	667	595	603
Electricity/Stain	1077	729	724	686	615	622
Gas Paint	443	345	357	372	317	341
Gas Stain	462	364	376	391	336	360

Table A5 Life cycle costing of aluminium clad timber and timber windows at a London location with 6 different glazing compositions with four different running options gas paint, gas stain, electricity paint and electricity stain - domestic applications

Timber windows						
	4-16Air-4	4-16Air-e4	4-16Ar-e4	4-10Kr-e4	e4-16Air-4Air-e4	e4-16Ar-4-16Ar-e4
U-Value (W m^{2}-K)	3 6	2.1	2.0	1.7	1.6	1.5
Costs (£)						
Capital	143	154	173	209	162	193
Electricity	839	476	453	385	363	339
Gas	242	139	133	113	106	100
Painting	90	90	90	90	90	90
Staining	180	180	180	180	180	180
Totals						
Electricity Paint	1072	720	716	684	615	623
Electricity/Stain	1162	810	806	774	705	713
Gas Paint	475	384	395	412	358	383
Gas Stain	565	474	485	502	448	473

Al-clad Timber windows						
	4-16Air-4	4-16Air-e4	4-16Ar-e4	4-10Kr-e4	e4-16Air-4-16Air-e4	e4-16Ar-4-16Ar-e4
Capital	171	183	201	237	190	221
Electricity	839	476	453	385	363	339
Gas	242	139	133	113	106	100
Painting	14	14	14	14	14	14
Staining	33	33	33	33	33	33
Totals						
Electricity/Paint	1024	673	668	637	567	575
Electricity Stain	1043	692	687	656	586	594
Gas/Paint	427	336	348	364	310	335
Gas Stain	446	355	367	383	330	354

APPENDIX B

LIST OF PUBLICATIONS

- Asif, M., Davidson, A. and Muneer, T., *Embodied Energy Analysis of Al-Clad Windows*, Building Services Engineering Research & Technology, pp 195 199, 22, 3, 2001.

- Asif, M., Davidson, A., Muneer, T., Gollner, J and Collins, C., *Powder Coated Aluminium-Clad Windows: Characteristics and Performance*, Proceedings of the Conference, 'The Whole-Life Performance of Facades', Bath, pp 63-69, April 18-19, 2001.

- Asif, M., Davidson, A. and Muneer, T., *Life Cycle of Window Materials: A Comparative Assessment*, CIBSE National Conference, London, June 18, 2002.