Aluminium and Life Cycle Thinking

Towards Sustainable Cities

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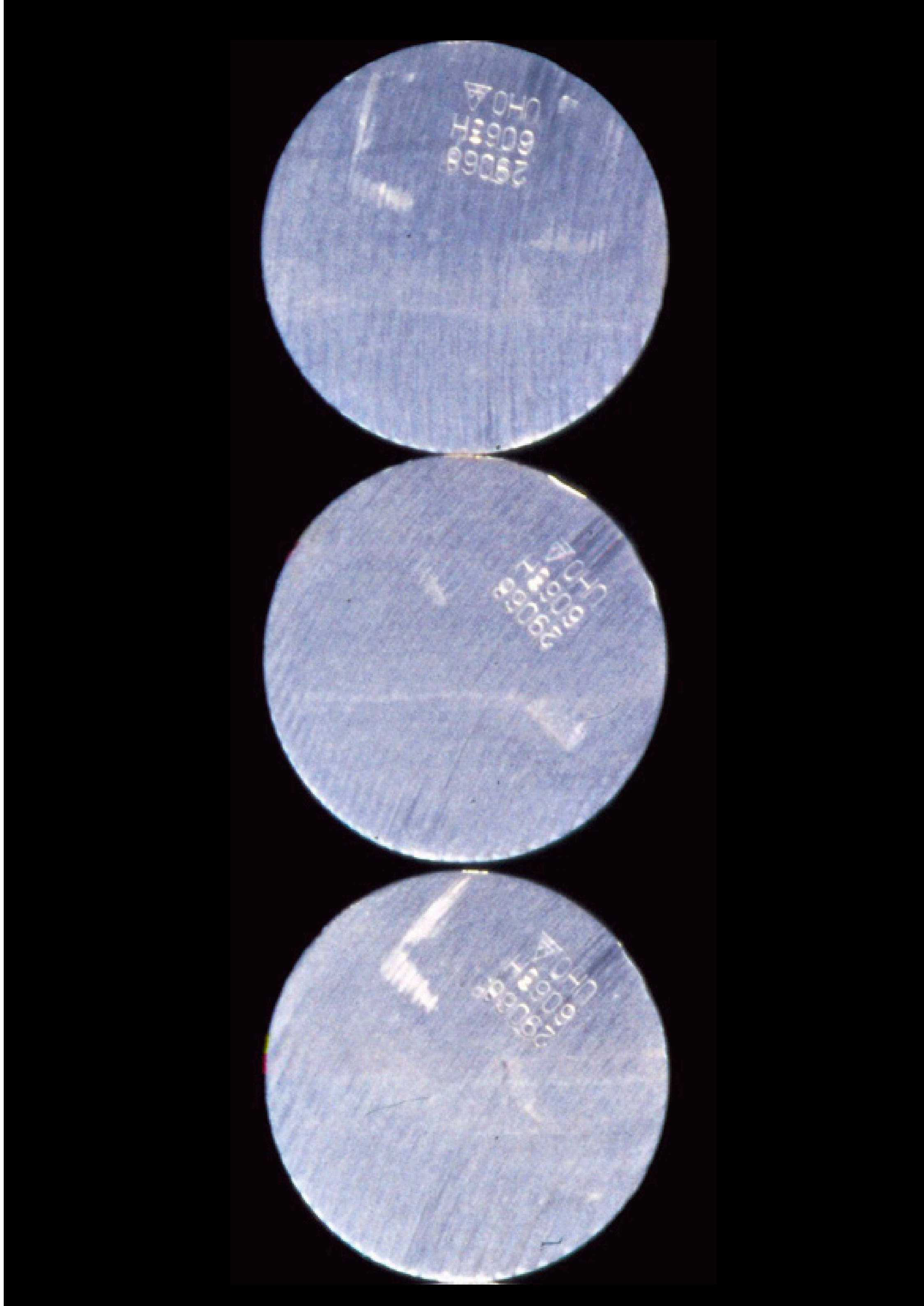

World Aluminium

International Aluminium Institute

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Front cover: Aluminium in construction for Cellophane House in New York, New York, USA (Architect KieranTimberlake, photograph by Albert Vecerka)

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Aluminium and Life Cycle Thinking

Towards Sustainable Cities

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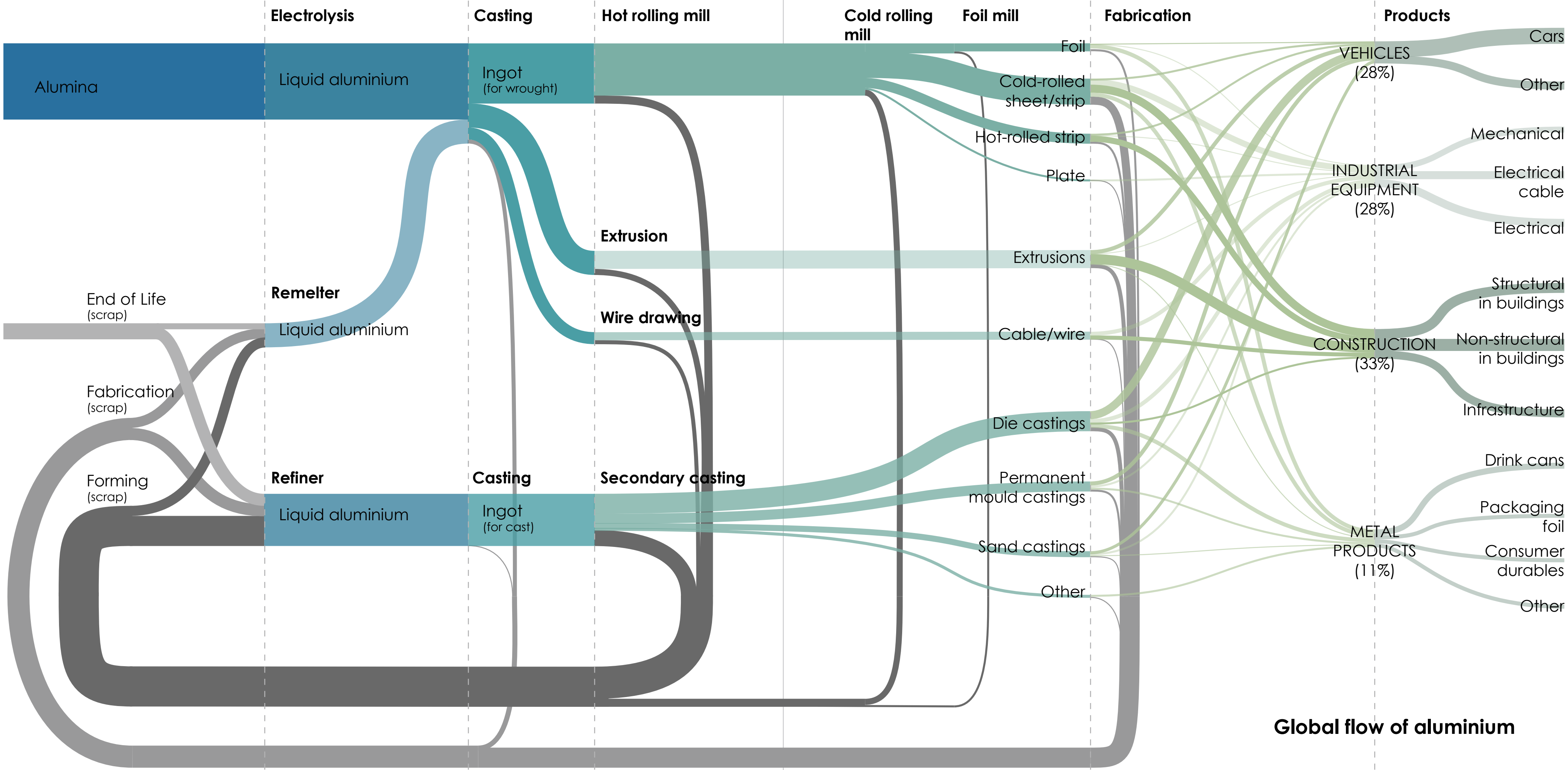


Global flow of aluminium

Fig 1.1 Global flow of aluminium (based on Allwood et.al, 201, additional mass flow data from IAI 2015)

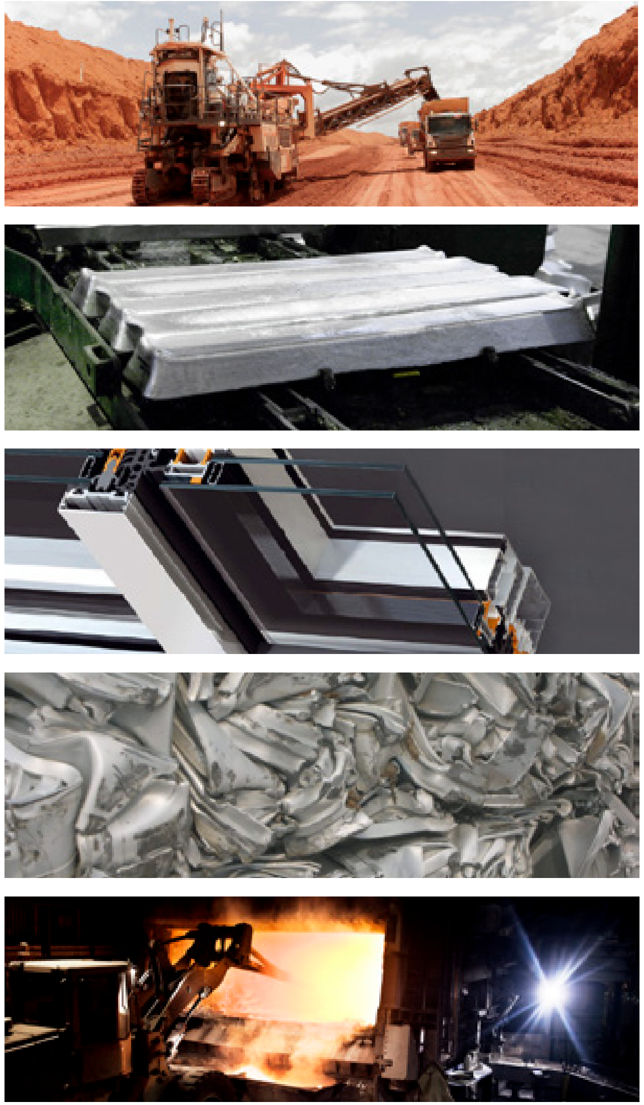


Fig 1.2 Life cycle stages for aluminium: mining, aluminium billets, use, reclamation, and remelt to recycle

Introduction

Towards Sustainable Cities - Quantifying the In Use Benefits of Aluminium in Architecture and the Built Environment serves to complement the relatively well-understood benefits of aluminium in other use sectors, such as transportation or packaging. A vital goal of this research is to quantify the potential contribution of aluminium towards the creation of sustainable cities: a key task as now over half of humanity lives in urban areas. *Towards Sustainable Cities* is funded by the International Aluminium Institute [IAI]. The programme was initiated by Chris Bayliss, Deputy Secretary General at IAI, and Michael Stacey of Michael Stacey Architects in Nottingham, England, in the spring of 2012. Programme collaborators include the Architecture & Tectonics Research Group [ATRG] of the University of Nottingham, and Stephanie Carlisle, Efrie Friedlander, and Billie Faircloth of KieranTimberlake in Philadelphia, Pennsylvania, USA.

Towards Sustainable Cities is structured as a series of studies on the primary benefits of aluminium's use in architecture–durability, recyclability, flexibility, lightness, efficiency, economy and sympathy (IAI, 2014). The first report, *Aluminium and Durability* (Stacey, 2014), amasses case study buildings that pioneered aluminium's use alongside exemplary historical and contemporary examples, to evidence life expectancy and **service life** (terms in bold are defined in the Glossary) for aluminium building components. The second report, *Aluminium Recyclability and Recycling* (Stacey, 2015), documents current building demolition protocols inclusive of the collection, reuse and **recycling** of building materials and components. It gathers case study buildings that demonstrate re-glazing/re-fenestration, over cladding, retrofit, deep-retrofit, and short-life building techniques–all dependent upon aluminium's economic value and ability to be collected and continuously recycled.

Aluminium and Life Cycle Thinking, the third report in the series, explores the environmental impact of durability and recyclability by investigating an aluminium building product's life cycle, or the stages through which it passes during its lifetime. Raw materials extraction, product manufacturing, use and maintenance, and processing at the end of a product's useful life constitute stages that may be examined in-depth to understand the environmental benefits attributable to an aluminium building product.

Life cycle thinking encourages the actors across the entire value chain – manufacturers, professional architects and engineers, contractors and building owners – to be mindful of the life history of any manufactured product, and more specifically, to understand the inputs (including resources such as energy and water) and outputs (emissions to the environment) that result from the transformation of materials into product, from product to service, and from service and to disposal. Life cycle thinking challenges architects, engineers, and contractors to make such mindfulness useful and valuable to the practice of ecologically responsible building design and construction.

If life cycle thinking is a framework through which a building product's life history is given consideration, **Life Cycle Assessment**, or LCA, is the modelling method used to quantify a product's environmental impacts. LCA models may be used to study specific questions regarding the environmental impacts of a given building product across selected stages of product life. Increasingly, LCA is a modelling practice being adopted by, or mandated to, architects and engineers during the design process in order to give consideration to environmental impact information during the selection of materials, components and assemblies (Bayer 2010, Al-Ghamdi 2015).

The creation of original LCA models complements the goals of *Towards Sustainable Cities – Quantifying the In Use Benefits of Aluminium in Architecture and the Built Environment*. Having established knowledge of the attributes durable and recyclable through the collection of case studies in the first and second reports, the LCA models created and interpreted in this report support 'if–then' investigations for selected stages. These increase a designer's awareness of aluminium's environmental impact, when for instance, she assumes a range of recycling rates; or assumes a given life span for a building component; or assumes various **energy mixes** during production. Ultimately, these models are provided to foster discourse on how life cycle thinking may be applied to decisions about aluminium's potential use in architecture.

Aluminium and Life Cycle Thinking is structured into seven chapters. Chapter Two: *A Life Cycle Approach* introduces the method of LCA and its application to building and construction products. It also identifies where aluminium may be found in a building. Chapter Three: *Life Cycle Assessment of Window Framing* describes the parameters and window assemblies used in the three LCA models that follow and that correspond to report chapters.

Chapter Four: *Modelling Recycling and Recyclability* investigates contributions of recycling through a comparison of four window framing assemblies. It asks: 'How do modelling choices with respect to the treatment of recycling affect the assessment of the assemblies' environmental impacts at end of life?' Chapter Five: *Modelling Durability* studies the same assemblies during their use to query the importance of maintenance and replacement impacts within the overall life span of a material assembly. It also asks, 'Which material elements of window framing assemblies contribute the most to environmental impacts for a given service/function?' Chapter Six: *Modelling Manufacturing* focuses on the production of aluminium window frames, asking: 'How does variability in the manufacturing process change the magnitude of the environmental impacts of aluminium building products over their full lifetime?'

The report concludes with a final chapter that discusses the implications of the findings associated with each LCA model on design decision-making with respect to environmental impact.

TWO

life cycle approach

Life Cycle Approach: Assessing the Sustainability of Aluminium in Buildings

Collectively, buildings have significant environmental impacts throughout their life cycles, from material production and initial construction through use and eventual demolition and disposal/recycling. Since the 1980s, architects, engineers, building owners and industry have primarily focused on reducing the operational energy use of building systems as the primary means of reducing environmental impacts. As architects and engineers continue to strive to make buildings less energy intensive to operate, increasing attention is being paid to another source of environmental impacts: those associated with building materials and construction processes.

Understanding the full impacts of buildings and construction requires examination of the full building system life cycle, including impacts that occur far from the building site in both space and time. Concrete, metals, wood, plastics and other materials have complex supply chains involving extraction, transportation and manufacturing processes that are consumptive of resources and cause emissions to the atmosphere, hydrosphere and pedosphere. Architects, engineers and specifiers are often aware of materials and their properties, but how can these materials' **embodied environmental impacts** and the potential they have to reduce environmental impact through intelligent design, long life or recyclability be measured? How can material assemblies containing dozens of materials be compared to one another? How can designers understand the trade-offs between low impact materials and durability? What role does manufacturing or recycling play in the total life cycle impacts of construction materials, and by extension, architectural design?

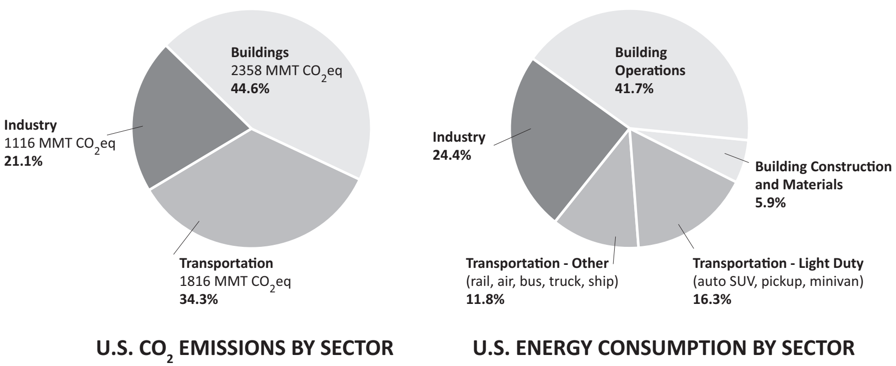


Fig 2.1 U.S. CO_2 Emissions and Energy Consumption by Sector (data based on Architecture 2030 and U.S. Energy Information Administration, 2012)

Life Cycle Assessment

Life Cycle Assessment [LCA] offers a rigorous, quantitative means of exploring the sustainability claims, resource use and environmental impacts of products from cradle to grave. LCA provides a means of exploring the environmental impacts and benefits associated with each stage of a product's life cycle – including material sourcing and manufacture, maintenance and use, as well as disposal, recycling and reuse – through a structured methodology of tracking material inputs and outputs across a product's life cycle. While LCA methodology is by no means a comprehensive metric of sustainability or environmental performance, it is an important and effective tool for guiding nuanced and informed comparisons of complex products and systems across a diverse range of impact categories, ranging from **global warming potential** to **acidification potential**.

While Life Cycle Assessment has been in use for over two decades, its application in the building and construction industry is relatively recent (Bayer et al. 2010, Crawford 2011, Simonen 2014). To date, the majority of construction-related LCAs have focused either on simplified models of whole buildings (with approximate values for an estimated bill of materials) or on the assessment of isolated building materials, e.g., steel, concrete, flooring, paint. Complex assemblies composed of numerous materials, such as curtain walling, windows and doors, roofing assemblies and structural systems, are just beginning to be better understood and modelled through the application of nuanced LCAs.

Fig 2.2 Aluminium and glass curtainwall compose the three principal faces of this tower, at Center City Building, University of North Carolina at Charlotte, USA, designed by KieranTimberlake. A pattern of transparent, fritted, and opaque panels screen solar radiation while maximizing natural light and views and working seamlessly with a concrete and steel structure

Fig 2.3 Glass and aluminium curtainwall at Brockman Hall for Physics at Rice University, Houston, Texas, USA, designed by KieranTimberlake

With the development of **Environmental Product Declarations** [EPDs] and other codified methodologies for conducting product-based LCAs, practitioners have begun to grapple with the resolution and specificity that LCA offers while also struggling to make sense of the often technical language and abstract results found in documentation that treats environmental impact information as a sort of 'ingredient list' or 'nutrition' label.

While there can be value in establishing an approximate carbon footprint or other environmental metric for a material or product, the real power of LCA as a tool for designers comes from its utility as a comparative assessment methodology that allows for nuanced comparisons of different material assemblies that serve the same function in a building, while respecting each option's unique material attributes and design logic. Furthermore, modelling practice in LCA is far from fixed or rigid (UNEP/SETAC 2011, PE International 2014). The detail captured in a comparative LCA model, and the ability to fine-tune the modelling process to a very specific mode of inquiry, allows for a productive exploration of a wide range of comparative research questions related to design choices, material selection, manufacturing processes, durability of assemblies, geographic variability of recycling rates and product life-times, as well as the relationship between building detailing and end-of-life scenarios.

Integrating a broader view of the material life cycle to include use and end-of-life stages is particularly important when evaluating materials that require a high initial resource or energetic investment but that have the potential to save resources through their use, reuse and recycling or energy recovery at end of life. These stages must also be treated with great care when different materials are compared, to make sure that a model is recognizing the limitations and opportunities nascent in material attributes. Just as cost analysis has been used by the design community to understand that products with higher first-costs may be less expensive to a client over the long term, LCA has the capacity to illustrate the environmental impacts of building assemblies beyond those associated with operational energy efficiency or initial material investment - *the total environmental cost of ownership*.

The Stock and Flow of Aluminium Through Buildings

In order to examine the potential contribution of aluminium to architecture, we must understand not only how flows of aluminium into buildings contribute to their embodied environmental impacts, but also how stocks of aluminium in buildings contribute to their performance over the full life span of the building. A considerable amount of the global stock of in-use aluminium is found in buildings. Recent mass flow modelling by the International Aluminium Institute [IAI] indicates that more than a third of aluminium currently in productive use is found in buildings (IAI 2015a). That aluminium takes a number of forms, both readily visible and hidden from sight. Aluminium can be installed as a gutter or a piece of trim; in building products, such as solar panels or light fixtures; or in complex building assemblies, such as curtain walling or window framing. In each case, aluminium is selected for one or more of its attributes, such as its light weight, long service life, reflectivity, conductivity, strength, formability or low maintenance requirements.

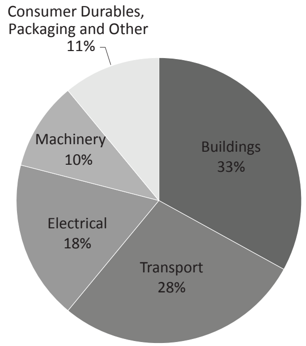


Fig 2.4 Distribution of aluminium in productive use by sector (data based on IAI 2015)

Each of these applications represents a different contribution to the overall flow of aluminium through a building, and the product's service lifetime is important to the evaluation of its contributions to the building's environmental impacts. Some of these applications of aluminium have short lifetimes - they are products that come in and out of a building over a period of months or years. Others are longer-term flows that remain integral to the performance of the building over its entire life span. Generally speaking, the aluminium products with the largest amount of mass, such as structural systems and façade systems, will be in place for most (if not all) of the building life, while applications with smaller mass will flow through the building much more quickly. Aluminium can also be a minor but critical part of a product with another base material, for example as an ingredient in the high-performance film in an insulated glass unit [IGU] or aluminium fasteners and hardware in a piece of wooden or composite millwork. An incandescent light bulb with an aluminium socket will likely have a shorter residence time than the pendant, with aluminium housing, in which it is placed, which in turn will be in the building for less time than the aluminium track from which it hangs.

Much of the available research on aluminium tends to focus on singular products or on aluminium as a raw material. From a design perspective, it is important to view aluminium as part of a complex building system. From a life cycle perspective, the role a material plays in the performance of a building is key to contextualizing the environmental impacts associated with the use of that material. When building materials, assemblies and even whole buildings are evaluated, a modelled building life must be assigned to serve as

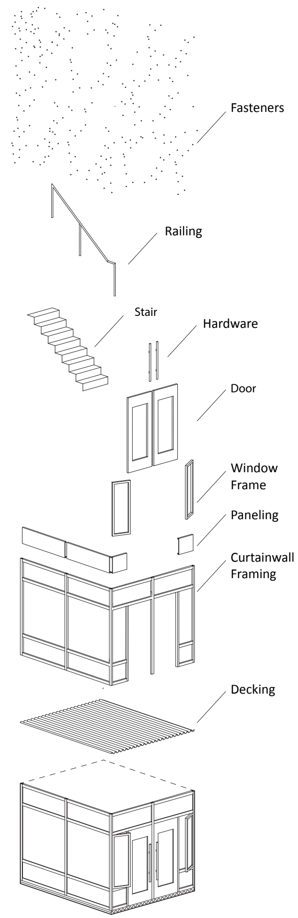


Fig 2.5 Exploded axonometric diagram showing typical uses of aluminium in the building sector

the duration of the study. Picking an appropriate duration of study for a Life Cycle Assessment of building materials and assemblies is difficult. If the study period is too short, the model may not accurately capture the relationship between long-life and short-life materials flowing through a building system. If the modelling period is too long, it adds increased uncertainty and may not be comparable with other previous studies.

While there is no globally agreed upon estimate of 'typical' building life for LCA, many studies use time periods of 60-80 years to assess building components, systems and full buildings. While some buildings and building components clearly last far longer than this estimate (Stacey 2014), these figures are deemed to represent an average building lifetime, and their use allows for comparison across studies of various building systems and materials (Preservation Green Lab 2012, US Department of Energy 2010).

Presently, none of the international LCA standards mandate the use of a particular typical building life, allowing practitioners the freedom to build models that best test their particular study questions and represent project or site specific considerations. Additionally, it has become more common for studies to approach questions from a holistic perspective, combining Life Cycle Assessment with other metrics, such as Life Cycle Costing [LCC]. Consistency in time periods between modelling techniques is another important consideration.

As the practice of LCA becomes more widely used in the building and construction industry, such factors may become codified and standardized over time. Several standards, such as 2012 International Green Construction Code (IgCC), LEED v4, BREEAM, Green Globes, Green Star, Green Building Evaluation Label: Three Star, and 2010 California Green Building Standard Code (CALGreen), have adopted whole-building LCA and require whole-building models to be run for a minimum of 60 years.

Life Cycle Stages of Aluminium Products

For the purpose of LCA, products are examined in four distinct stages, each associated with particular processes, inputs and outputs. This practice helps to clarify the scope of the analysis and to clarify where and when impacts occur across a product life cycle. Breaking down results into life cycle stages allows researchers to fine-tune their assessments and allows designers opportunities to understand, improve and critique the impact of design decisions. While there are a number of ways to divide life cycle stages, the following list describes the stages used in this study and gives some examples of questions that may be of concern to designers associated with each stage.

The **extraction** stage is primarily concerned with the mining and production of raw materials used in primary aluminium production. Important considerations in this stage are the impacts of the technologies and processes used for mining, producing, and transporting bauxite–including geographical location of mines, technologies used for energy production, and mining runoff control. While the extraction of raw materials for aluminium affects a large land area, its total environmental impacts are far lower than production processes, such as smelting (Atherton 2007, PE International 2014). The driving questions for this stage of analysis ask: 'What materials are in the product? How are those materials obtained?'

The **production** stage encompasses the refining, smelting, casting, and manufacturing required for the production of aluminium as well as the impacts of the building construction processes associated with the product. Also commonly referred to simply as manufacturing and often combined with material sourcing and extraction, this is also the stage in which primary and recycled aluminium are combined to make new products. This stage is of particular interest to designers, as it capturers a wide range of operations (such as casting, cutting, assembly and finishing) necessary to transform a relatively raw material into a wide range of products. It is also, in the case of aluminium, the stage with potentially the greatest environmental impact. In production, aluminium is often combined with other materials that contain their own extraction and supply chain impacts. The production stage also includes packaging and any transportation necessary to the manufacturing supply chain. Interrogation of this stage seeks to answer the questions: 'By what processes is the product made? What are the impacts associated with those processes?'

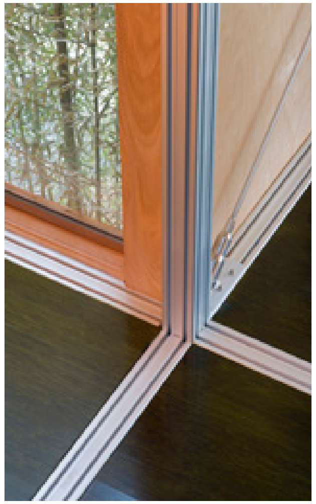


Fig 2.6 Exposed structural aluminium framing and interior detailing at Loblolly House, a private residence in Maryland, USA, designed by KieranTimberlake

The **use** stage for an aluminium product includes any use, maintenance, replacement, and repair regime impacts over the duration of the study. This stage is where trade-offs between material choices such as the life cycle costs, performance, maintenance, durability, or constructability may come into play. Also included are any processes or materials associated with product use, such as operational energy or water use. When the duration of study is set to the life cycle of a building, rather than a single product **guarantee** period, such concerns become even more relevant. This stage focuses on the questions: 'Is durability important for this product? What inputs are needed for this product to function? Is it more efficient to do a lot of maintenance or to replace the product more frequently?'

Finally, the **end-of-life** stage includes the demolition, sorting, collection and treatment of aluminium products after they are no longer in use. As most aluminium used in building and construction is recycled at the end of life due to its high economic value (van Houwelingen 2004), LCAs often assign credits to scrap that is returned to material streams by calculating the avoided environmental burden that would have resulted from the production of primary aluminium. The relative impacts per life cycle stage vary considerably by material and by **impact category**. For example, for materials such as asbestos or lead, end-of-life processing and disposal will play a significant role in total life cycle impacts. For aluminium and others with high energy intensity from production or high recycling rates, these impacts are minimal and often overshadowed by credits from material returned to the product stream. Analysis of this stage requires answers to the following questions: 'What will recycling and **reclamation** practices be at the end of product life? How should benefits of reclamation and recycling be quantified?'

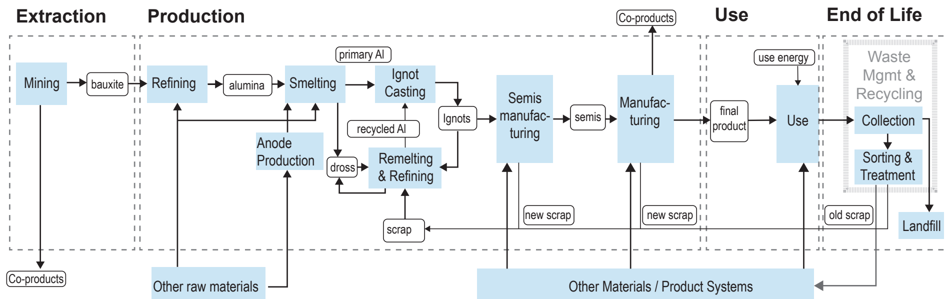


Fig 2.7 Simplified visualisation of the cradle to grave life cycle of aluminium products. Only primary processes and flows are shown in this diagram for ease of visualisation

Recycling and Recycled Content in Aluminium Building Products

Modelling the benefits of recycling is particularly difficult for metals like aluminium that may be repeatedly recycled, as the recycling process creates a linkage between diverse product lives. Metals, such as aluminium, do not experience significant product losses in the use stage nor degrade during the recycling process, and their properties do not change between primary and recycled material. It is estimated that during the remelting process, approximately 1-2% of material is lost, primarily due to oxidisation (Das et al. 2010). Recycled aluminium requires up to 95% less energy to produce than primary metal and produces only 5% of the greenhouse gas emissions (IAI 2009), as the most energy-intensive processes are related to refining and smelting (IAI 2013a).

As discussed in further detail in Report Two of this series, titled *Aluminium Recyclability and Recycling*, recycling aluminium is both efficient and cost effective. Reclaimed and recycled aluminium are valuable commodities with robust markets and industry processes that facilitate collection, processing and the full movement of reclaimed materials back to market as ingots, extrusion billets or new rolling slabs. Since savings in energy are also often savings in cost, economic incentives support very high global reclamation rates and also significant environmental benefits (van Houwelingen 2004, Das et al. 2010).

Approximately one third of European Union aluminium demand is met through recycled sources, and nearly all aluminium products are made with some percentage of recycled aluminium, a quality that fluctuates with product requirements, global and local scrap availability, market demands, and sector constraints. The recycled content of aluminium products can vary by location, segment, application and time due to a number of factors, including economic history, construction and demolition practices, and geopolitics. European products produced today have a comparatively high recycled content due to the availability of scrap aluminium from a large number of older buildings that are now undergoing demolition or refurbishment, as well as access to mature scrap markets and technologies and mature product markets, such as castings for use in transport, (Rombach et al 2012, IAI 2014).

While including recycled content in aluminium products is cost effective and environmentally beneficial, manufacturers are constrained by the availability of scrap as the global demand for aluminium far outweighs the availability of recycled aluminium. Even with the assumption of 0% growth in aluminium demand, recycled content of aluminium will not exceed 40% globally before 2050, as recycled content is limited in large part by recycled

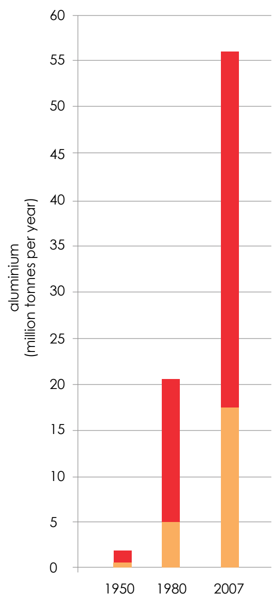


Fig 2.8 Global demand for aluminium met from primary (red) and recycled aluminium (orange) in 1950, 1990, and 2007 (data based on IAI 2009)

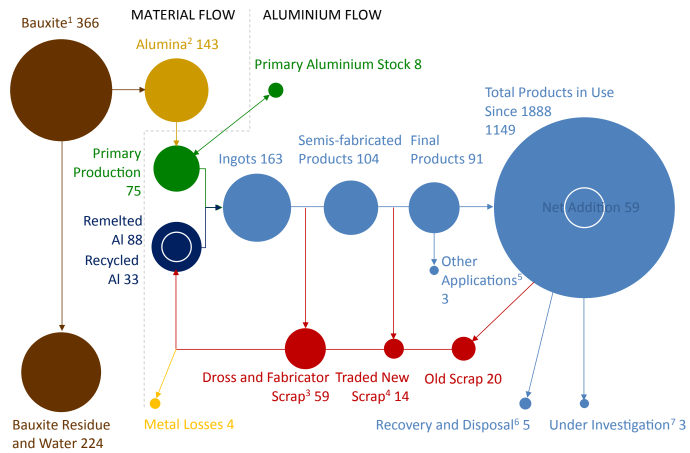


Fig 2.9 Global aluminium mass flow, 2020

aluminium material availability (Rombach 2013). This is particularly relevant in the building and construction sectors, as the service life span for aluminium components can be particularly long (>50 years). Larger components tend to have the longest service lives, creating a lengthy delay between demand for aluminium in construction and availability of aluminium scrap from buildings for recycling. For a more extensive discussion of this topic, see Report Two *Aluminium Recyclability and Recycling*.

How should architects and engineers regard recycled content and the environmental benefits of aluminium recycling? If aluminium is almost infinitely recyclable, should the environmental impacts of its manufacturing be assigned to a singular use, and if so, how?

As aluminium retains its qualities and value over multiple uses, the distribution of environmental impacts from primary aluminium production must be equitably and consistently shared between these uses. For the purpose of LCA models, two primary methodologies are used in the building and construction sector for allocating the impacts and benefits of recycling between products (Atherton 2007, Leroy et al. 2012, EAA 2013, PE International 2014). Each approaches credits for the benefits of recycling slightly differently, placing emphasis on a different part of the product life. The result is a shift in the boundary being drawn between the various lives of the material.

These two methodologies, known as the **Recycled Content** (**Cut-Off**) **Method** and the **End-of-Life Recycling** (**Avoided Burden**) **Method**, will be explored in Chapter Four: *Modelling Recyclability & Recycling*.

THREE

life cycle assessment of window framing

Life Cycle Assessment of Window Framing

The following chapters in this report contain a series of modelling studies, using comparative Life Cycle Assessment to explore key issues in the environmental impacts of building materials. The three case studies focus on: Recycled Content and End-of-Life Recycling scenarios; service life, maintenance and durability; manufacturing inputs and service life sensitivity analysis. All three LCAs make use of a simple and common architectural component, window framing, as the object of comparison, allowing for exploration of multiple materials and assembly techniques.

Why Windows?

Windows present unique challenges and opportunities. They represent under-studied, complex assemblies that contribute both to the embodied environmental impacts of building components and also to their energy performance. Window framing is available in a variety of base materials, for example metals, woods, plastics, and composites, each with their own attributes and design requirements. The four assembly types considered in this study allow for a thorough exploration of several critical questions in the use of life cycle environmental impact characterisation on material selection, detailing and design considerations.

Windows constitute an important and relatively costly building component. Composed of several materials and sub-assemblies, they play a significant role in the performance, appearance and use of a building over time. While a building may have a total life of more than a hundred years, most window framing assemblies do not last as long, requiring maintenance and replacement throughout the life of a building. Each framing type investigated in these case studies has complex, but manageable life histories - all of which factor into the decision-making of designers and building managers when making purchasing and detailing choices. From maintenance costs and incremental replacement, to recycling credits and regional sourcing, a wealth of questions can be explored through this seemingly simple component.

Literature exploring window framing or other complex architectural components from an environmental impact perspective is sparse. While a small number of LCAs for window framing have been conducted, the majority of assessments have approached window framing as an object or product, rather than an assembly playing a sustained and essential role in a larger building system. Such studies tend to count only materials contained in the first installation, and discount the effects of use, replacement and end-of-life scenarios on the environmental impacts over the life cycle of a building (Asif 2002, Sinha & Kutnar 2012, Salazar & Sowlati 2008).

While some attention has been paid to the energy performance of window assemblies, window framing, and curtain walling over time (Sinha & Kutnar 2012, Kim 2011, Citherlet 2000), few studies adequately examine use-stage impacts or consider the effects of window frame repair, replacement, recycling or disposal. Additionally, existing literature on window framing and façades singles out embodied energy as the primary environmental metric worthy of study, with the effect of excluding other impacts. By contrast, this comparative study aims to expand discussion of the role of use-stage and end-of-life impacts on total environmental accounting of window framing assemblies and to more accurately display the material attributes and design consequences of materials such as aluminium, wood, and PVCu.

Recently, a comparative LCA commissioned by the European Aluminium Association and Schüco (Mösle 2015) have expanded the range of questioning to examine window framing as part of a holistic evaluation of environmental, social, and economic variables. In the EAA/ Schüco study, window framing is examined for its contributions to the sustainability of a full building system, and is functionally defined by its performance in relationship to floor area. The study herein expands on that work by focusing on direct comparison of the environmental impacts of window assemblies in isolation from variables of the larger system, such as thermal comfort and building energy demand. While metrics such as full-building energy performance and aesthetics are indeed important, they require design and site-specific analysis that allows them to be tied to larger system considerations rather than a single component or assembly such as window framing material.

The design and specification of window assemblies are not, of course, the only factors affecting the total environmental impacts of a building. However, glazing assemblies remain an essential component of building design - and they warrant detailed study. Far from attempting to place a single impact score on a material assembly, the case studies in this report delve into focused questions about materials and assemblies that directly influence design decisions.

Fig 3.1 Frame types (top to bottom): aluminium, wood, aluminium-clad wood, PVCu

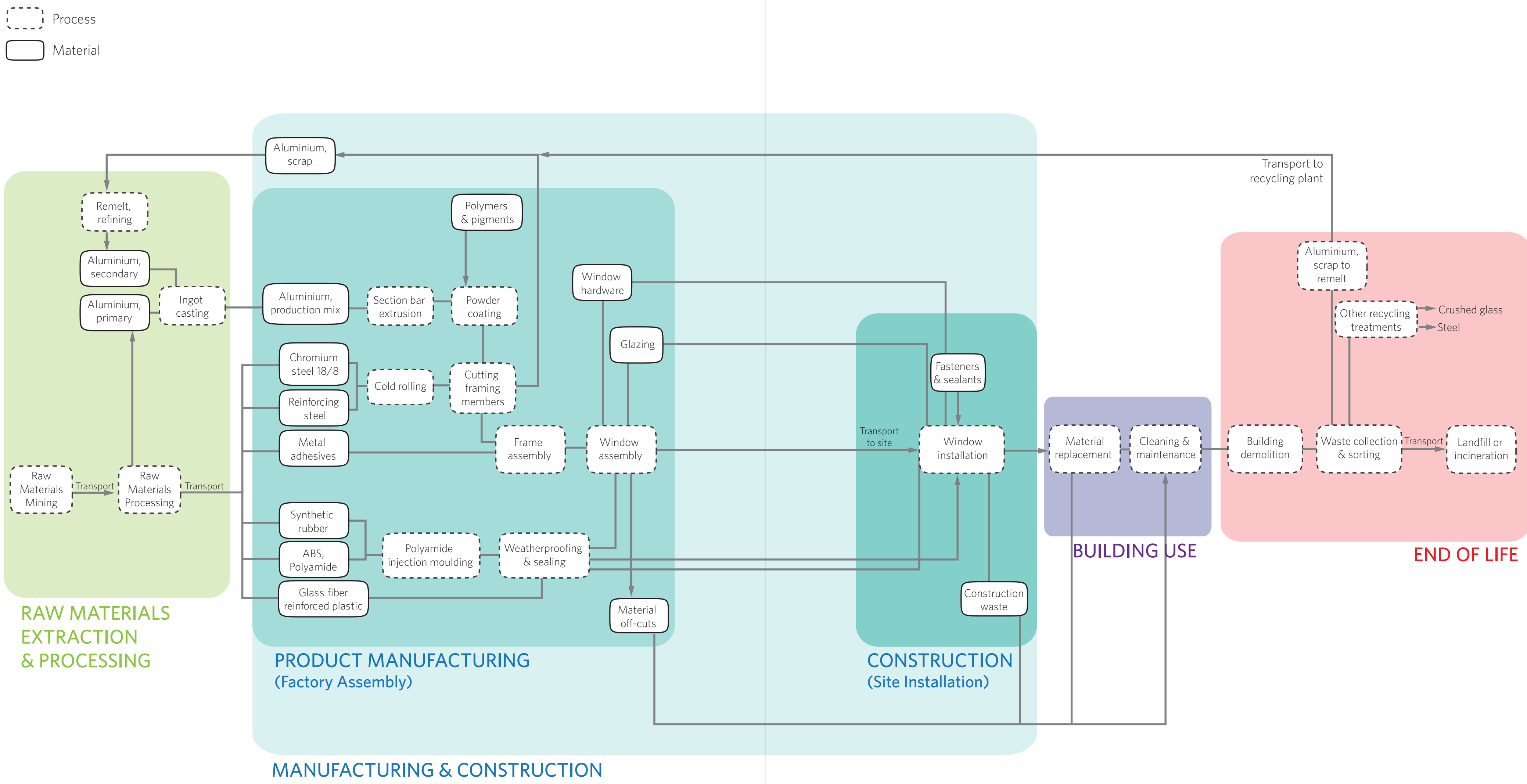


Fig 3.2 Life cycle stages (**ISO 14040**) and system boundaries for a typical aluminium window frame

LCA Methodology

The following chapters use the methodology below to conduct comparative Life Cycle Assessments on window framing. Chapters Four and Five compare assemblies of aluminium, wood, aluminium-clad wood, and PVCu window frames. Chapter Six focuses only on variables in aluminium product manufacturing and therefore models only aluminium window frames. Any deviation or elaboration on the methodology is discussed within each chapter.

Goal and Scope Definition

The primary objectives of the following Life Cycle Assessments are:

- To explore key issues in the environmental impacts of building materials through the use of a common architectural component in order to offer insight that is transferable to more complex building systems.
- To compare the total environmental impacts of multiple material choices and assembly techniques in order to understand the impact of design decisions beyond building-level energy efficiency.
- To identify the variables within the life cycles of window frames that have the greatest influence on the total life cycle environmental impacts of the assemblies.

Functional Unit

The **functional unit** of the study is a window frame required to produce 1 m2 of visible glazing, with similar thermal performance (U-values between 1.5 and 1.6 W/m2K), over a building life span of 80 years. A sensitivity analysis was also undertaken with building life spans ranging from 40 to 100 years in Chapter Six.

Studied Objects

The study compares four window frame types: aluminium, wood, aluminium-clad wood, and PVCu. Galvanized steel and other less common framing types are outside of the scope of this study. Glazing is not included in the frame assembly as it can be considered to be equivalent across window types.

While calculating environmental impact of various materials and processes during the extraction and production stages is relatively straightforward, inclusion of differential use-stage impacts of window frames in an assumed building within a cradle-to-grave LCA is much more difficult. To normalize for performance and to assure functional equivalence over the building lifetime, all window assemblies have been designed to yield similar energy performance (air-to-air heat transmission value) and visible light transmission. The reference window size for all assemblies is: 1.6 x 1.3 m^2 with a visible frame surface of 0.45 m^2 in the case of metal-clad, PVCu, and wooden frames, and 0.48 m^2 for the aluminium window (Weidema 2013).

System Boundaries and Delimitations

The analysis accounts for the full life cycle of each window, including material manufacturing, use and maintenance, and eventual end of life. Window frame assemblies include primary frame material and all additional materials - gaskets, internal hardware, sealing, coating and finishing - required for assembly and installation up to a 1% **cut-off factor** by mass, with the exception of known chemicals that have high environmental impacts at low levels. In these cases a 1% cut-off was implemented by impact.

Manufacturing of window frames is distinct per frame material. The production of wooden and aluminium-clad wooden frames includes cutting, profiling, finishing, plugging and stopping, joining and fitting of pieces. PVCu window frame production includes moulding and plastic extrusion, cutting and welding of plastic members, and aluminium section bar extrusions. Aluminium window frame construction includes the extrusion and anodising of aluminium, section bar rolling of steel, material finishing and sealing (Weidema 2013). Background data, including impact of electrical energy and other raw materials processing for production, are included in the respective inventory figures.

Transportation - from manufacturing location to construction site and from construction site to processing site for disposal or recycling - is assumed to be highly variable and not particularly impactful, but it remains an important step in the product life cycle and was included and tested with a standard uncertainty analysis.

End-of-life impacts and credits were modelled using a disposal scenario generated to reflect the collection and processing of construction and demolition [C&D] disposal streams (Doka 2007, Weidema 2013), and as described further in Report Two. In the modelled scenario, several materials are diverted for recycling, including paper (85%), glass (94%), aluminium (90%), steel (75%), PET (80%) and PVC (20%). In the case of aluminium and plastics, collection rates are based on European averages (Doka 2007) and reflect sector-specific collection rates (IAI 2014, VinylPlus 2014).

Material recovery rates (i.e. post-collection rates) are based on global industry averages (Weidema 2013). Of the remaining materials not diverted for recycling, 88% (by mass) were assumed to be sent to incineration and 12% sent to landfill, in accordance with European averages (Weidema 2013). Materials such as wood and PVCu, for which a significant amount of energy is generated during incineration, received a credit for the avoidance of energy generation that they offset through reuse. Further documentation of waste and disposal scenarios can be found in the appendix.

Window Framing Assemblies

The study compares four window frame types: aluminium, wood, aluminium-clad wood, and PVCu. All frame assemblies include primary frame material, coatings (paint, polyurethane, powder coating), any necessary weather stripping material, gaskets or sealants. The material quantities for each window assembly are documented in detail in the appendix.

Aluminium Frame

The aluminium window framing assembly consists of four primary parts: frame, hardware, the weather sealing and finish. The entire assembly weighs 50.7 kg. The frame portion of the assembly is made of anodised aluminium, extruded plastic, and reinforcing steel, as well as the packaging and processing required for those materials.

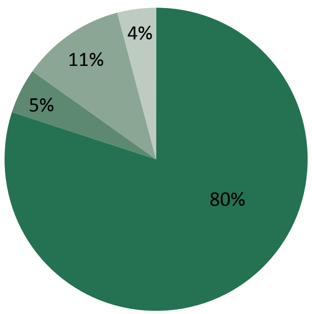


Fig 3.3 Aluminium frame: composition by Mass (kg) of assembly

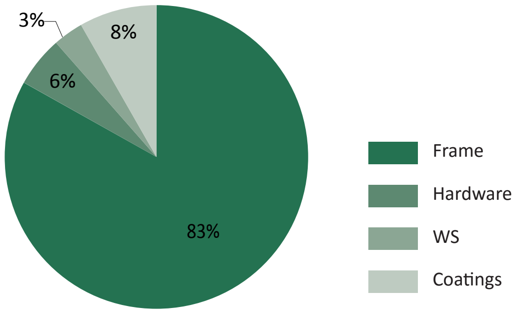


Fig 3.4 Aluminium frame: contributions to total Global Warming Potential (kg CO_2 eq) for initial installation

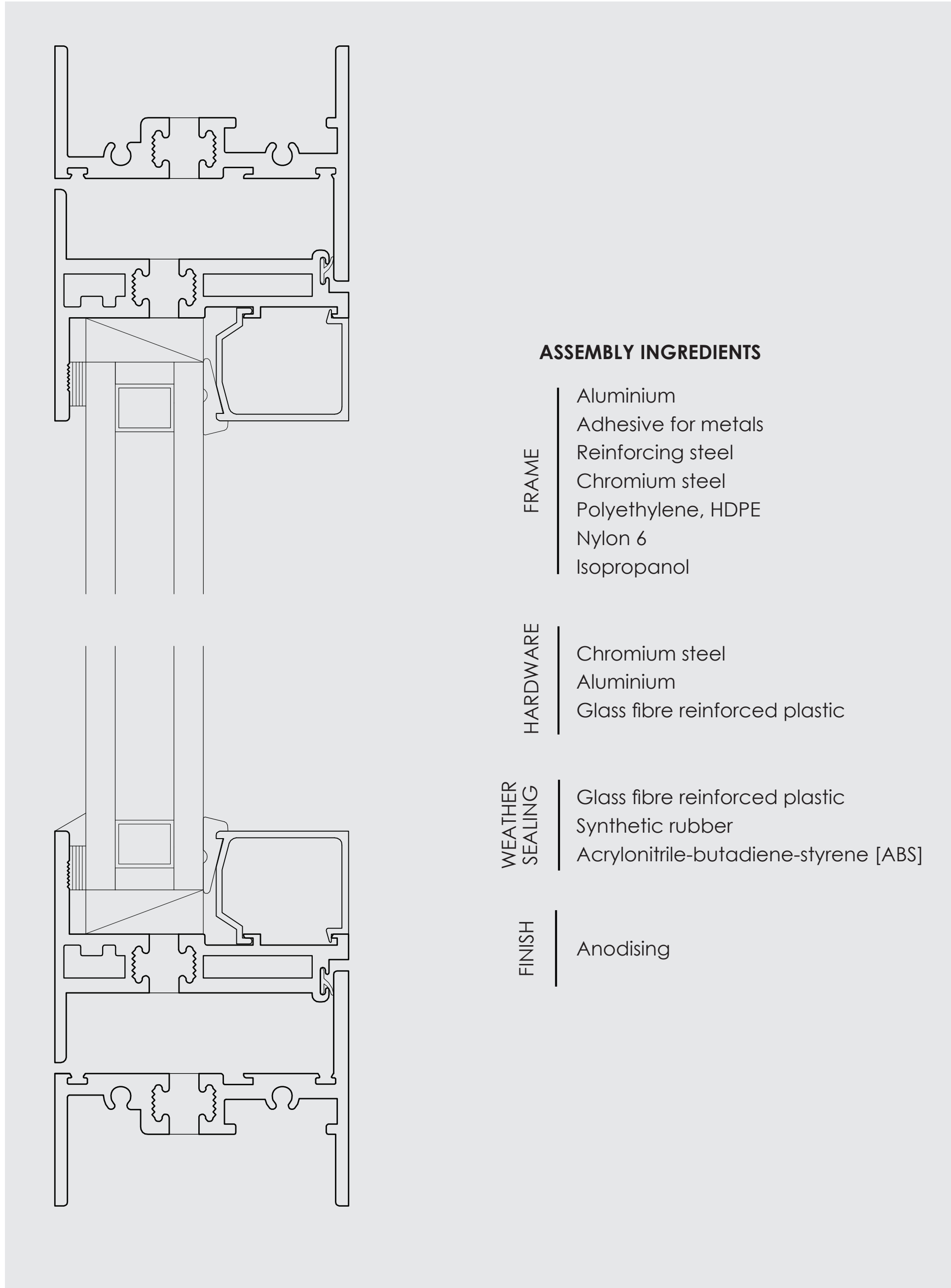


Fig 3.5 Aluminium casement window detail: section detail and ingredients list

Wood Frame

The wood window framing assembly consists of a frame, hardware, weather sealing and a urethane paint finish. This assembly is significantly heavier than the aluminium frame, weighing in at 106.2 kg. Embodied in this assembly are the processes for kiln drying the wood, timber sawing, joining, fitting, surface finishing, hardware production, and all the transportation associated with production stages. It is assumed that the frame is made primarily from softwood, with hardwood making up only 1% of the wood components by volume (Weidema 2013). In accordance with general European production processes, scrap wood is assumed to be collected and recycled as wood pellets.

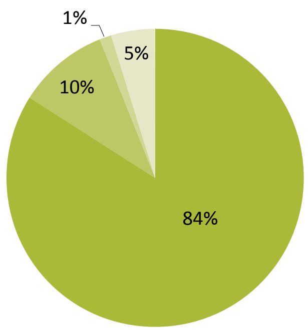


Fig 3.6 Wood frame: composition by Mass (kg) of assembly

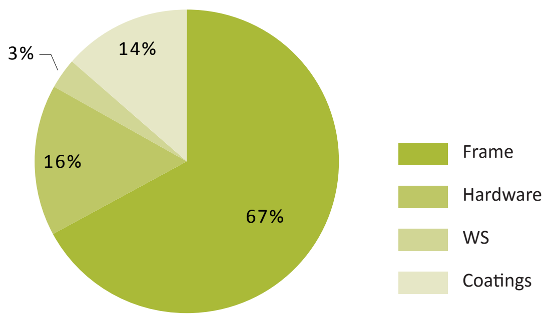
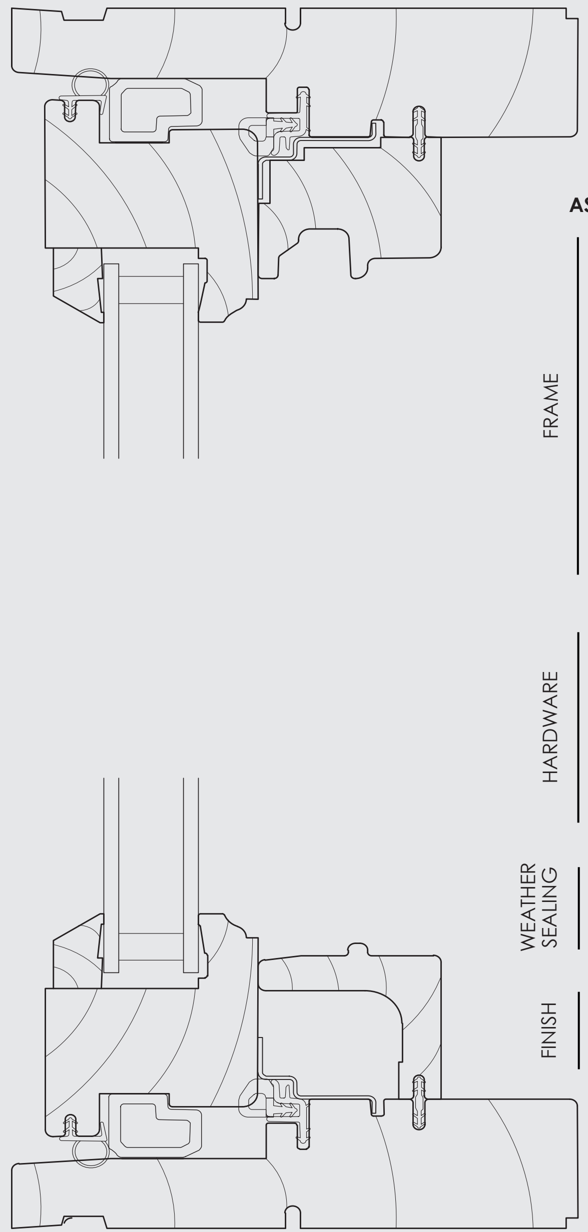


Fig 3.7 Wood frame: contributions to total Global Warming Potential (kg CO_2 eq) for initial installation



ASSEMBLY INGREDIENTS

FRAME
- Sawn timber
- Aluminium
- 1-butanol
- Acetone
- Titanium dioxide
- Toluene
- Isopropanol
- Methyl ethyl ketone
- Propylene glycol
- Benzimidazole-compounds
- Alkyd resin, 70% in white spirit
- Melamine formaldehyde resin

HARDWARE
- Aluminium, cast alloy
- Steel, low-alloyed
- Zinc, primary material
- Copper
- Polyvinylchloride [PVC]
- Polyethylene, LDPE
- Polypropylene

WEATHER SEALING
- Synthetic rubber
- Nylon 66

FINISH
- Alkyd paint, 60% in H2O
- White spirit
- Acetone

Fig 3.8 Wood casement window detail: section detail and ingredients list

Aluminium-clad Wood Frame

The aluminium-clad wood window framing assembly is similar to that of the wood window framing assembly, with the addition of aluminium extrusions cladding the exterior face. This assembly, weighing 111.1 kg, is slightly heavier than the wood window frame due to the addition of the aluminium cladding. The aluminium-clad wood window framing assembly is finished with a polyester powder coating on the aluminium face and a painted interior wood face.

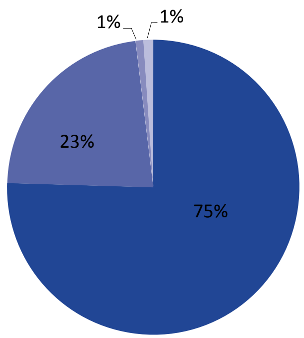


Fig 3.9 Aluminium-clad wood frame: composition by Mass (kg) of assembly

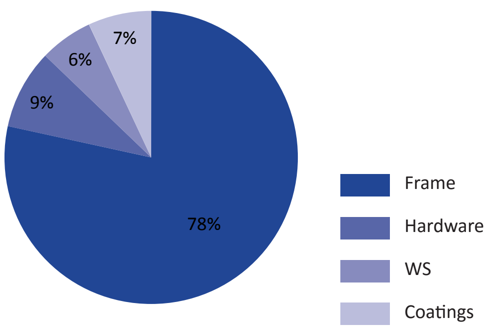
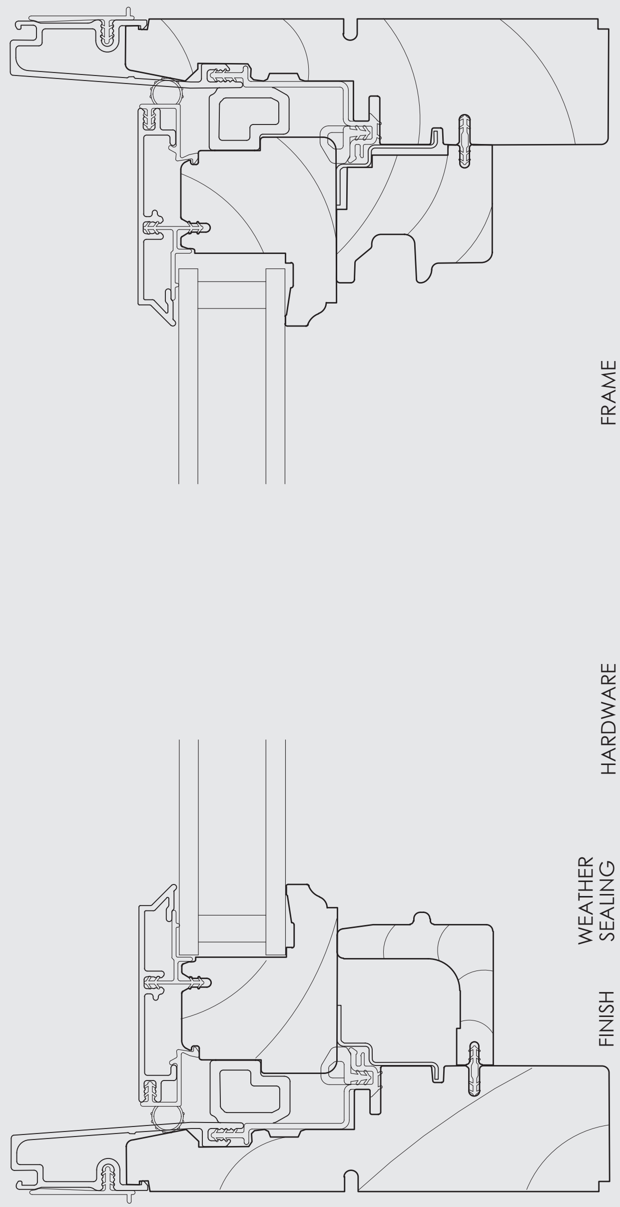


Fig 3.10 Aluminium-clad wood frame: contributions to total Global Warming Potential (kg CO_2 eq) for initial installation



ASSEMBLY INGREDIENTS

FRAME
- Sawn timber
- Aluminium
- 1-butanol
- Acetone
- Titanium dioxide
- Toluene
- Isopropanol
- Methyl ethyl ketone
- Wood pellets
- Propylene glycol
- Benzimidazole-compounds
- Alkyd resin, 70% in white spirit
- Melamine formaldehyde resin

HARDWARE
- Aluminium, cast alloy
- Steel, low-alloyed
- Zinc, primary material
- Copper
- Polyvinylchloride [PVC]
- Polyethylene, LDPE
- Polypropylene

WEATHER SEALING
- Synthetic rubber
- Nylon 66

FINISH
- Alkyd paint, 60% in H2O
- White spirit
- Acetone

Fig 3.11 Aluminium-clad wood casement window detail: section detail and ingredients list

PVCu Frame

The PVCu window framing assembly is unique in that it does not include any paint or coatings for the frame, as PVCu is generally left unfinished. This assembly is the second-lightest (heavier than the aluminium frame assembly) at 91.3 kg. The frame assembly includes the necessary reinforcing metals as well as the plastic components and metal hardware. Manufacturing includes formulation of plastics, injection moulding extrusion, assembly and welding of framing members.

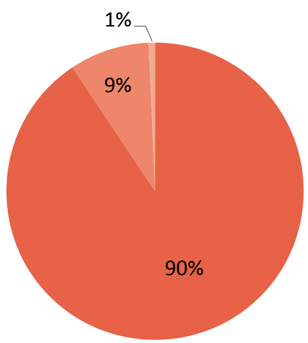


Fig 3.12 PVCu frame: composition by Mass (kg) of assembly

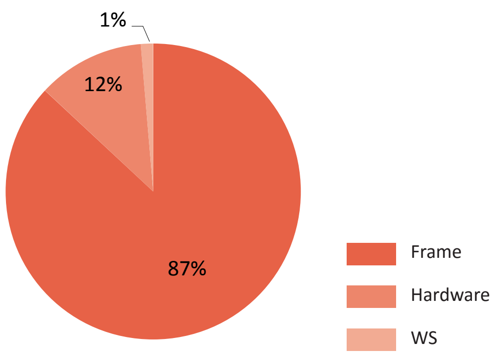


Fig 3.13 PVCu frame: contributions to total Global Warming Potential (kg CO_2 eq) for initial installation.

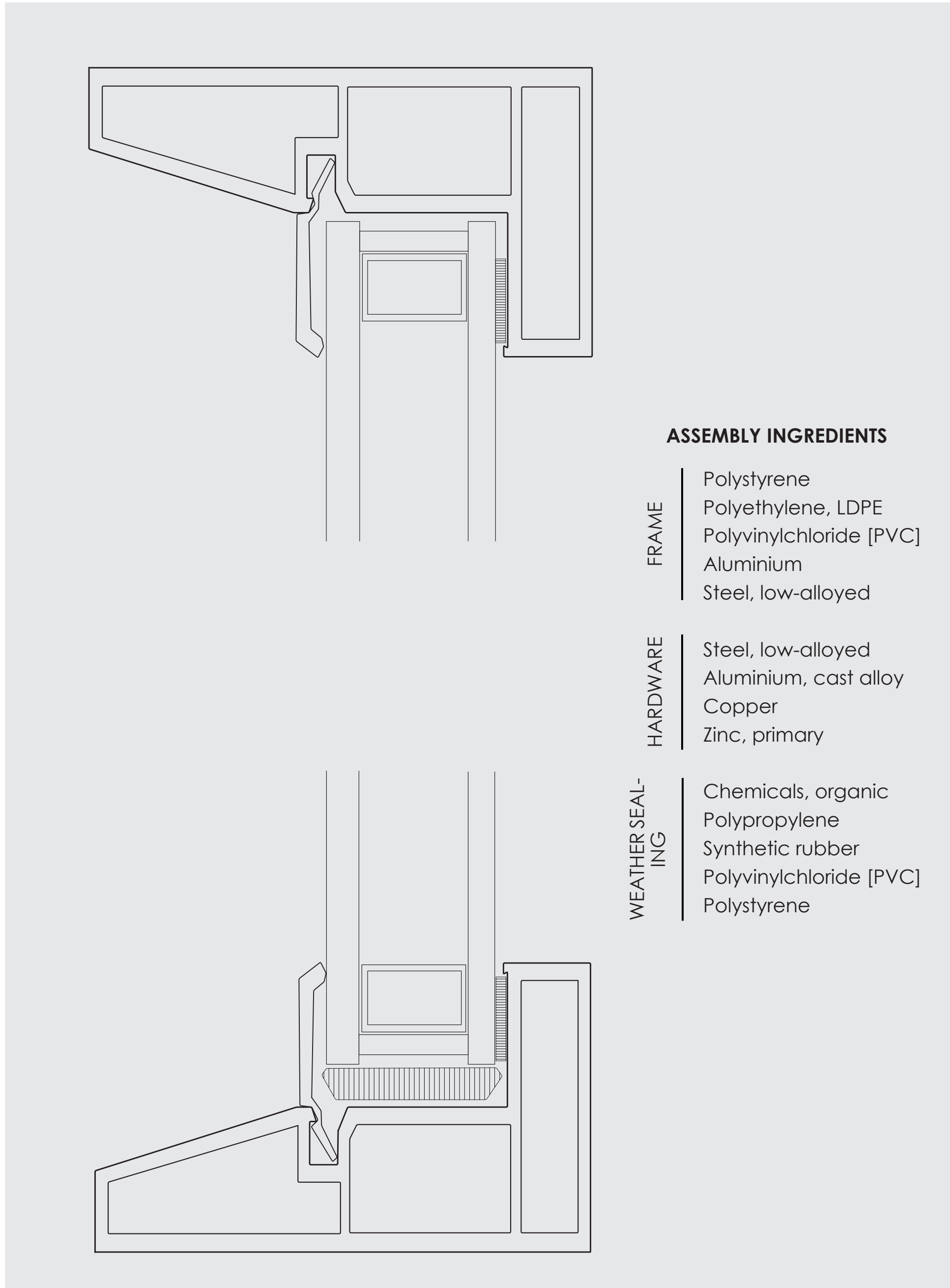


Fig 3.14 PVCu casement window detail: section detail and ingredients list

Impact Categories

Environmental impacts were calculated using the U.S. Environmental Protection Agency [EPA] Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (Ryberg et al. 2014). In the assessment, six impact categories were tracked, in accordance with industry harmonization efforts: global warming potential, **ozone depletion potential**, acidification potential, **eutrophication potential**, **photochemical smog creation potential** and depletion of fossil energy resources (PE International 2014). The metrics by which these are measured are explained in the table below. Human and environmental toxicity results are not reported due to very high levels of statistical uncertainty in the underlying life cycle inventory methodology and characterization.

The impact categories in TRACI allow for the quantification of environmental burden associated with typical stressors, such as chemical emissions to air and water or fossil fuel use. The method used by TRACI characterizes such impacts at the midpoint, measuring the environmental system change, such as a depletion of the ozone, rather than the endpoint, for example increased rates of skin cancer and crop damage, in order to minimize the amount of uncertainty associated with forecasting the effects of environmental system change (Bare 2002).

Global warming potential	kg CO_2 eq	Potential global warming based on chemical's radiative forcing and lifetime, based on the potency of greenhouse gasses relative to CO_2.
Ozone depletion	kg CFC-11 eq	Potential to destroy the protective ozone layer in the earth's stratosphere due to harmful emissions like chlorofluorocarbons, halons, etc. Equivalencies are based on chemical's reactivity and lifetime.
Photochemical smog formation	kg O_3 eq	Potential for the creation of ground level ozone due to the interaction between nitrogen oxides (NOx) and volatile organic compounds (VOCs) resulting in human health and ecological impacts.
Acidification	kg SO_2 eq	Acidification includes the processes that increase the acidity of water and soil systems by releasing [H+] or equivalents.
Eutrophication	kg N eq	Potential to cause eutrophication measured as a product of nutrient factor (relative strength of influence on algae growth in aquatic ecosystems) and transport factor (probability that the release arrives in the aquatic environment in which it is a limiting nutrient).
Resource depletion (fossil fuels)	MJ	Depletion of non-renewable fossil fuels. The present model includes a non-site-specific characterization of fossil fuels sources and use.

Fig 3.15 Impact categories reported according to TRACI 2.1 characterization scheme (Data based on EPA 2012)

Data Sources

For the purpose of comparison of results across window types, the life cycle inventory data used in this study represent global industry averages (Weidema 2013) for each of the four framing types.

The LCA model was built using SimaPro, a professional LCA modelling software. Life cycle inventory data used for this assessment came from the Ecoinvent database (Weidema, 2013). Window assemblies and material quantities are based on a dataset collected by the Swiss Federal Laboratories for Materials Science and Technology (EMPA) that covers manufacturing practice for high-performance windows manufactured in Switzerland and Germany between 1996 and 2004. It is the stated assumption of EMPA that the dataset is relevant for European manufacturing practices.

For all sub-materials contained in an assembly, regional or global production mixes have been used to best represent typical industry practice rather than the performance of any one manufacturer or manufacturing location (Weidema, 2013). Data has not been adjusted to reflect regional differences in the models in Chapters Four and Five. All changes made to manufacturing production mixes are explicitly stated in Chapter Six.

The documentation for the original window frame entries in the Ecoinvent database differentiates specific quantities of metals, plastics, and composite materials used for production of frames, fittings, sealing, and coating. Hence, custom assemblies were created to represent 'recoating', 'resealing', and 'replacement of hardware' for each frame type in order to generate nuanced maintenance and replacement regimes. Likewise, waste scenarios were adjusted from Ecoinvent's database to represent scenarios for disposal of materials such as replacement hardware, fittings, and weather proofing applied during the use stage for the purposes of maintenance and replacement. Waste scenarios were also adjusted to reflect different reclamation practices in the third LCA model in this report, Chapter Six: *Modelling Manufacturing*.

FOUR

modelling recyclability & recycling

Modelling Recyclability & Recycling

How do different LCA methodologies model the recycling of aluminium, wood, aluminium-clad wood and PVCu window framing? Which is the most suitable for understanding the complete life cycle environmental impacts of building assemblies?

These questions arose during the investigations initiated in Report Two of this series, *Aluminium Recyclability and Recycling*.

Recycled Materials in LCA

Recycled materials, by definition, are materials connected to more than one product or assembly. Recycling, the process of preparing a material so that it can be reused or refashioned, represents the cyclic stage of product life. Many industrial materials, such as plastics and chemicals, are produced from the by-products of other processes or other saleable products, and materials such as aluminium can be processed and repurposed with very little waste while retaining the material properties of the original material. Such interconnectedness between products and product lives presents a challenge for Life Cycle Assessment, as a boundary needs to be drawn to separate the processes and inputs of one material use from another (Atherton 2007, PE International 2014).

When examining the topic of recycled content in metals, this is a particularly tricky subject, as one must make decisions about how to allocate the impacts associated with initial manufacturing and extraction between the potentially infinite uses and re-uses of a highly recyclable material. In LCA terminology, **allocation** refers to the method by which the impacts connected to one or more products, assemblies, or services may be divided. Particular challenges arise when determining how to allocate the benefits and process impacts of recycling between products with a share of primary and recycled material.

As the impacts associated with primary and recycled aluminium have dramatic differences in their carbon footprint and other environmental impact indicators, see Chapter Two for further discussion, there are clear environmental and economic benefits to utilizing recycled content. The question that remains is how to best allocate environmental impacts, especially in determining which use should receive the credit for savings associated with recycling.

There is presently a high variability in how recyclable building components are modelled in terms of allocation and end-of-life impacts. The two primary approaches to recyclable materials in Life Cycle Assessment are the **Recycled Content Method**, also known as the Cut-Off Method and the **End-of-Life Recycling Method**, also known as the Avoided Burden Method. The Recycled Content Method is recommended by several national standards, including **EN15804**, while the End-of-Life Recycling Method is recommended by ISO standards and the ILCD Handbook. Each modelling practice is internally consistent, but represents a different view of the relationship between primary and recycled aluminium (as well as other materials) by focusing on either the recycled content going into the product stream, or the recovered material coming out (Frischknecht 2010).

The differences in approach are expressed by the location of the system boundary. The Recycled Content Method allocates all impacts for resource extraction and refining to the first life of the material and only the impacts for recycling to the production stage of the recycled material. By contrast, the End-of-Life Recycling Method adds credits for environmental benefits resulting from end-of-life recycling, which reduces the need for virgin material in the next use of the material. In practical terms, this means that for the Recycled Content Method, recycled content of the material in question is the key indicator of environmental impact, while for the End-of-Life Recycling Method, the recycling rate at the end of product life is the key metric.

NAME OF APPROACH	SCENARIO 1: RECYCLED CONTENT	SCENARIO 2: END-OF-LIFE RECYCLING
Alternate names	Cut-Off Method	Avoided Burden Method
Key indicator of environmental impact	Recycled content	Recycling rate at end of life
System boundary	Cut-off rule applied on recycled materials exiting the system (analysis looks only at the single product use)	Includes impacts of the recycling processes
Who gets the benefits?	Recycling benefit given to the product using recycled materials	Recycling benefits given to the product providing material for recycling
Who carries the burden?	First use receives the burden of materials (primary and recycled); recycled materials at end of life do not carry energy or process burdens	First use receives credit for avoiding demand of primary material; recycled materials now carry impacts for energy and process of recycling
Indications for policy	Promotes the consumption/use of recycled materials	Promotes the production/preservation of recyclable materials

Fig 4.1 Recycling credit allocation method comparison

Many studies have shown that the selection of allocation method has a major influence on model results. Yet there has been much debate over which method is most appropriate in LCA (Frischknecht 2010, Hammond & Jones 2011, Trenton 2012), particularly with respect to metals, which do not change their properties between primary and further uses and where availability of scrap is limited.

The Recycled Content approach is particularly difficult to apply in the case of aluminium (Atherton 2007, Liu and Müller 2012, PE International 2014). It requires precise knowledge of the percentage of recycled content by mass in an assembly, which may be difficult to determine when availability of scrap is variable and scrap is incorporated in aluminium production melts with no change to performance properties (EAA 2013, Schlesinger 2013, Puga 2009). On the other hand, using the End-of-Life Recycling approach may be inaccurate in predicting reclamation rates and impacts of recycling at the end of life when the product lifetime is longer, such as in a building (Hammond & Jones 2011)– especially since recycled aluminium's high economic value incentivizes increased recycling rates and improved technology development. In light of this uncertainty, it is standard practice to construct models that utilise current recycling recovery data as a credible baseline, even though recovery methods may be more or less efficient in the future.

The metals industry has recommended that the End-of-Life Recycling Method is more appropriate for discussions involving the recycling of metals in order to promote net global conservation of material and resources rather than directing limited recycled feedstock towards specific products (Atherton 2007). However, others have suggested that differences in LCA results using the two methods may point to one method being more useful for comparative LCA across materials and the other when using LCA as an industry-specific, policy-influencing tool (Ekvall 2001, Wardenaar 2012, Huang 2013). In part, this may be explained using a window frame assembly example. Aluminium (or any other highly recycled material) – retains its high value and physical properties in future uses of that material while the other window framing materials under comparison do not necessarily retain their primary material properties after recycling and may benefit more from focusing on the recycled content used in production of the assembly.

Through the following model comparing window framing assemblies, LCAs are used to explore the application of these two

methodologies to building assemblies in an attempt to determine which is more suitable for understanding the environmental impacts of building products and materials.

Description of Approach

This model uses LCA as a tool to compare aluminium, wood, aluminium-clad wood, and PVCu windows using the two allocation methods described above to determine which method more accurately depicts the material attributes and design consequences of product choices. The model is run to represent an 80-year building life. The windows are assumed to have a basic maintenance regime, in which a building manager or owner follows commonly prescribed maintenance practices aimed at reaching a longer lifespan for the window while maintaining a high level of window performance. Depending on the frame type, maintenance practices (described in the appendix) may include refinishing and periodic replacement of damaged or worn out components, such as weather stripping, sealants, gaskets, or hardware, at regular intervals. Questions of variability in maintenance practices and useable life are explored further through modelling in Chapter Five: *Modelling Durability* and through case studies in Report One of this series, *Aluminium and Durability*.

Scenario 1 uses the Recycled Content Method to allocate the full burden of production to the first life of the material and only considers the impacts of the recycling process for the share of the product that is from recycled sources. In this scenario, aluminium assemblies are modelled with a mix of 67% primary aluminium and 33% recycled aluminium from a mix of old and new scrap (EAA 2013). While higher recycled content blends could be achieved, this scenario aims to represent a typical commercially available

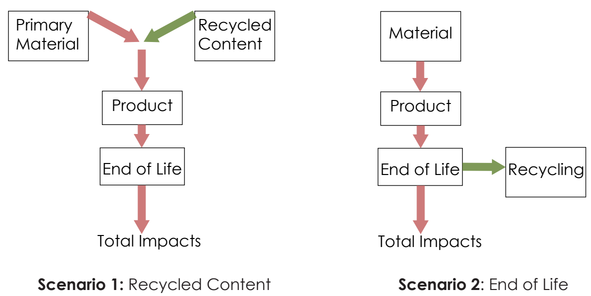


Fig 4.2 Diagrams describing the allocation methods used for the Recycling Content and End of Life Allocation methodology

European aluminium window. Other regions would likely have a window with lower recycled content, an issue discussed in Chapter Six *Modelling Manufacturing*.

Scenario 2 employs the End-of-Life Recycling Method, giving credit for future recyclability and reclamation by passing the environmental impacts of the initial production to subsequent uses. This gives the credit for recycling to the product of study for avoiding the impacts that would have been associated with a product made of entirely virgin material. All assemblies are modelled using end-of-life disposal scenarios tuned to present product selection, construction, and demolition/waste diversion and recycling rates. Aluminium, steel, paper and plastics receive credits associated with materials diverted from the waste stream and recycled at end of life, while wood products receive credit from energy recovery associated with incineration. In this methodology, the specific recycled content is not measured, as this would constitute double counting.

For all frame assemblies, a disposal scenario was generated that is representative of the collection and processing of construction and demolition [C&D] disposal streams (Doka 2007, Weidema 2013). In this disposal scenario, materials are diverted for recycling, including: paper (85%), glass (94%), aluminium (90%), steel (75%), PET (80%) and PVC (20%). In the case of aluminium and plastics, collection rates are based on European averages (Doka 2007) and reflect sector-specific collection rates (IAI 2014, VinylPlus 2014). Further documentation of waste and disposal scenarios can be found in the appendix.

While there is variability in the effective rates of recycling, per geography and material application, these conservative baseline figures were deemed sufficient for a comparison of methods. The significance of variation in recycling rates is explored further in Chapter Six: *Modelling Manufacturing*.

All remaining materials not diverted for recycling are then modelled using a waste processing typical of European averages, with 88% of material sent to incineration and 12% sent to landfill (Weidema 2013). Materials such as wood, for which there is energy generated during incineration, receive a credit for the avoidance of energy generation that they offset as well as the burden for the impacts of the incineration.

Results

The results clearly indicate that the choice of allocation method has a significant impact on the magnitude of environmental impacts the model associates with the material in question. Using the Recycled Content Method (Scenario 1), greater focus is placed on the avoidance of virgin material, as manufacturing and construction inputs make up a large portion of the overall environmental impacts. Using the End-of-Life Recycling Method (Scenario 2), greater focus is placed on material recovery at the end of product use, as materials receive credit for being able to replace virgin material in their next use. This makes PVCu appear significantly better across all categories under the Recycled Content Method than it does under the End-of-Life Recycling Method.

The difference in results for aluminium between scenarios is striking. While aluminium is never the most impactful option in Scenario 1, it is only the least impactful in two of the six categories. However, in Scenario 2, aluminium is the least impactful choice across all categories by a wide margin, never contributing more than a third of the impacts of the highest impact option, PVCu, and generally less than half the impacts of its closest competitor. This change can be predominantly attributed to the credit received for avoiding the impacts of manufacturing associated with primary material processing. As these are the life cycle stages with the largest environmental impacts in the aluminium life cycle, allocation of these impacts has a dramatic effect on the net impacts of the material assembly.

Aluminium-clad wood frames also benefit from a shift to Scenario 2. They are the most impactful in all categories except Acidification using the Recycled Content Method. However, they are the second-best choice across all categories except for Fossil Fuel Depletion when analysed using the End-of-Life Recycling Method. This is most likely due to the dramatic difference in environmental impacts for the aluminium cladding of the frame, which experiences the same benefits of environmental impact reduction as the primarily aluminium frame.

When comparing each material to itself between the Recycled Content Method (Scenario 1) and End-of-Life Recycling Method (Scenario 2), it is useful to consider the change in numerical value of the results in order to understand how the benefits of recycling are being considered. The largest changes were seen in aluminium across all categories except for fossil fuel depletion.

Scenario 1: Recycled Content

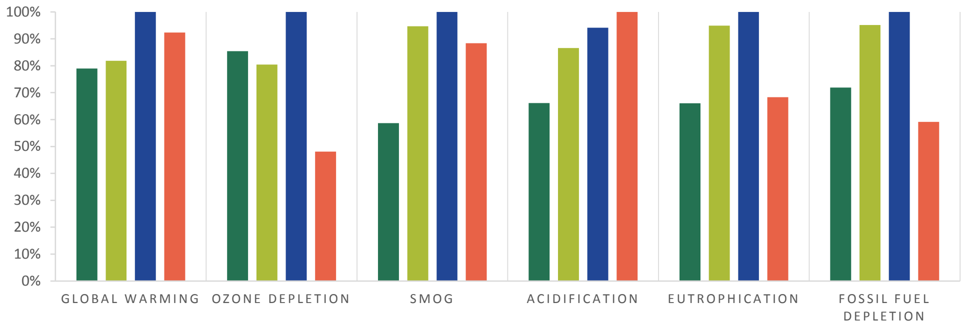


Fig 4.3 Comparative LCA results for each of the window assemblies in Scenario 1 (Recycled Content Method) across TRACI 2.1 impact categories

Scenario 2: End of Life

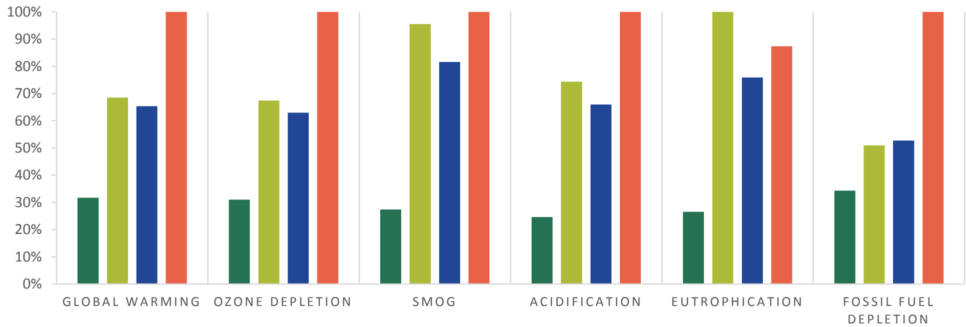


Fig 4.4 Comparative LCA results for each of the window assemblies in Scenario 2 (EoL Method) across TRACI 2.1 impact categories

- Aluminium
- Wood
- Aluminium-Clad
- PVCu

In particular, aluminium saw a reduction of 51%, 42%, and 39% in eutrophication, ozone depletion, and acidification, respectively, when the allocation method switched from Scenario 1 to Scenario 2. Aluminium also dropped in the global warming potential category by 38%. PVCu, on the other hand, was the only category to perform more poorly across all categories under Scenario 2. In particular, PVCu increased in the fossil fuel and ozone depletion categories by 59% and 40%, respectively.

Although most of the categories measured a reduction in embodied impacts for the majority of material assemblies in Scenario 2, each assembly had an increase in fossil fuel depletion. Aluminium increased the least (5%), with aluminium-clad wood and wood framing having an equivalent increase (10%) and PVCu increasing the most (59%). This increase can be attributed to the inclusion of end-of-life processes and impacts for recycling, including the transportation of materials, such as to and from the recycling plant.

Discussion

Although each scenario indicates that there are significant disparities between the environmental impacts per framing materials, the model results also demonstrate the magnitude of differences in results between the End-of-Life Recycling and Recycled Content methods. These differences point to two distinct approaches to design decision-making in the building and construction sector.

Evaluation of window framing materials and other complex assembly types, through methods that account for the full life cycle, creates the possibility for designers, consumers and manufacturers to make responsible and informed decisions about material selection and ongoing design development.

For highly recyclable materials such as aluminium, the emphasis nascent in each allocation method may promote particular practices in the industry, manufacturing, and design decision-making. As discussed in Chapter Two, the amount of recycled content currently available for aluminium products is constrained because demand for scrap is higher than supply due to the long lifetime of aluminium building products and the growing market for aluminium. For materials such as PVCu that can be recycled but presently have low collection rates and low market demand for recycled material, the system understanding highlighted in the End-of-Life Recycling Method may lead to increased efforts to promote material reclamation and recycling pathways in order to reduce environmental impacts (Atherton 2007).

Scenario 1: Recycled Content
Scenario 2: End of Life

Global Warming Potential

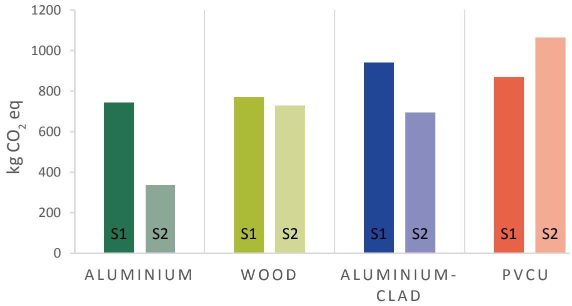


Fig 4.5 Comparing the results of Scenario 1 to Scenario 2 for Global Warming Potential

Ozone Depletion

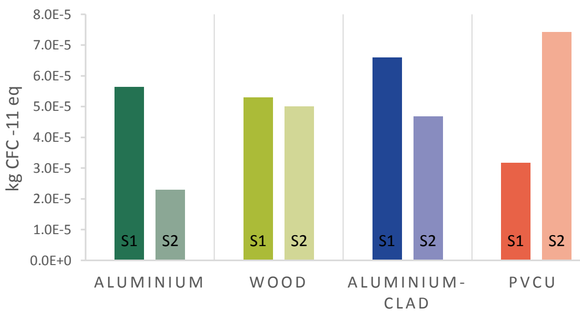


Fig 4.6 Comparing the results of Scenario 1 to Scenario 2 for Ozone Depletion impacts

Smog Formation

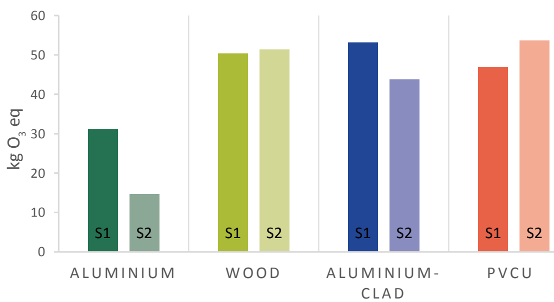


Fig 4.7 Comparing the results of Scenario 1 to Scenario 2 for Smog Formation (photochemical oxidants)

Acidification

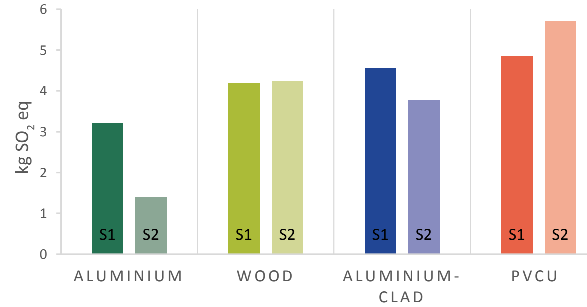


Fig 4.8 Comparing the results of Scenario 1 to Scenario 2 for Acidification impacts

Eutrophication

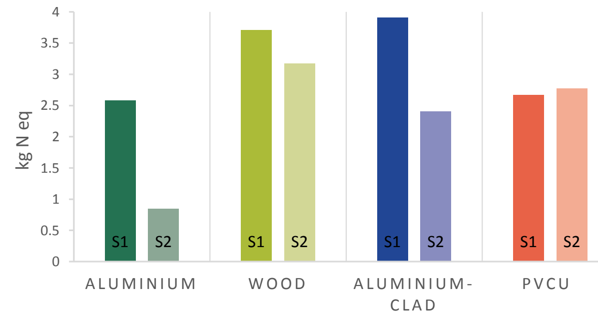


Fig 4.9 Comparing the results of Scenario 1 to Scenario 2 for Eutrophication impacts

Fossil Fuel Depletion

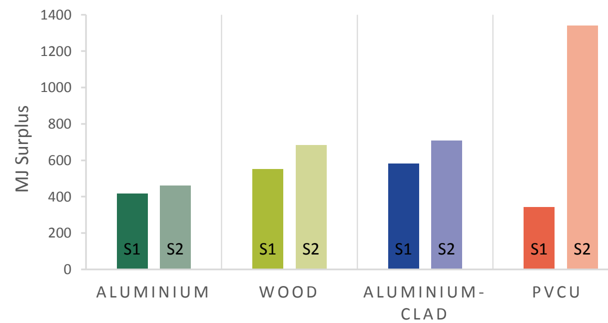


Fig 4.10 Comparing the results of Scenario 1 to Scenario 2 for Fossil Fuel Depletion

The Recycled Content Method promotes the consumption and use of recycled materials, encouraging designers to focus on obtaining products with as high a recycled content as possible. While this may allow one building to appear more sustainable than another because of a particularly high content of recycled aluminium, the global balance will remain the same, as demand for recycled content already cannot be fully met. In essence, this approach encourages designers to play a global game of musical chairs, in which one project may demand higher recycled content in its aluminium supply, but can only do so at the expense of another project. For other materials, an increased desire for recycled content may indeed increase competitiveness in circumstances where material recycling does not provide the same inherent financial savings to manufacturers.

Alternately, the End-of-Life Recycling Method promotes the production and preservation of recyclable materials, as the environmental benefits for recycling are given to the product providing the recycled material. Instead of encouraging designers to focus on their material source, this approach encourages life cycle thinking by privileging material reclamation, persuading designers to consider deconstruction and disassembly processes as an important part of sustainable practice when designing building details and assemblies. While it is difficult to predict precise benefits of reclamation and recycling after a long-life aluminium product is integrated into a building, such as in the structural system or curtainwall, this uncertainty may be quantified thorough application of sensitivity analysis using multiple recycling scenarios (EAA 2013). Placing the onus on designers to design for recovery for the benefit of the whole value chain is discussed further in Report Two of this series, *Aluminium Recyclability and Recycling*.

Fig 4.11 Demolition and material sorting. Philadelphia, PA, USA

FIVE

modelling durability

Modelling Durability

How does material durability and maintenance/replacement strategies associated with aluminium, wood, aluminium-clad wood and PVCu window framing affect a window frame's total environmental impact over the lifetime of a building? Which elements of window framing assemblies contribute the most to environmental impacts?

These questions arose during the investigations initiated for Report One of this series, *Aluminium and Durability*.

LCA as a Tool for Assessing Durability

For many LCAs conducted on building materials or products, use stage examinations have focused exclusively on operational energy. Questions of maintenance practices and material replacement have been insufficiently addressed in LCA work due to the difficulties associated with quantifying the benefits of physical properties such as durability (Liu and Müller 2012).

For windows, questions of durability and material replacement are particularly significant. Framing assemblies, described in Chapter Three, are composed of a number of materials serving different purposes and subjected to varying stresses and wear. Therefore, the act of window refurbishment and replacement is a significant and meaningful part of the building life cycle - and a growing topic of interest for high-performance building design and retrofit.

In published literature, the majority of LCAs conducted for window frames have focused on the manufacturing and end-of-life impacts as stand-alone products with no specified service life (Sinha & Kutnar 2012, Asif et al. 2007, Lawson 1995) or have shortened model timeframes to 40 or 50 years, so that they do not include significant maintenance or material replacement. Additionally, most EPDs are cradle-to-gate assessments, as

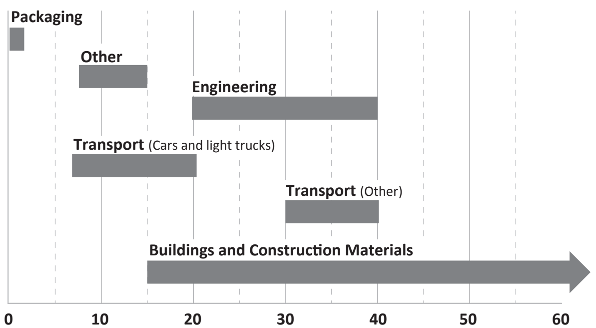


Fig 5.1 Estimated average use phase ranges for aluminium products in years (data based on IAI 2015)

described in Chapter Two, which leave out the question of use phase impacts entirely. This trend can, in part, be explained by the difficulty of approximating an accurate service life for window framing - a long-life product whose replacement can hinge on a number of factors, from aesthetics to performance to user needs. However, when examining material use on buildings that must achieve high performance standards for 80-100 years, the assumed service life of a component such as window framing does matter, as a single full replacement of an assembly will effectively double the product's life cycle impacts.

A first impact approach can create results that fail to account for the potentially significant impacts of maintenance and replacement activities, while also failing to credit materials for their durability and long life spans. Due to lack of available data, it has also become accepted practice for most academic LCAs to utilise service life figures from standard product guarantees, a practice that may skew results and disadvantage materials such as aluminium for which observed, in-place service life may be much higher than modelled, as observed in Report One of this series, *Aluminium and Durability*.

The consequence of material replacement also varies across material types depending on the percentage of environmental impacts attributed to various components and activities, such as the frame, hardware, weather sealing, and refinishing. Wholesale replacement is particularly significant for aluminium window frames made of primary aluminium, as they may have a greater environmental impact during their manufacturing stages than PVCu or wood, yet their durability and low maintenance requirements may improve their comparative environmental impacts when viewed from a building life cycle perspective. Wood window frames may have a low embodied environmental impact up to the point of installation because of the minimal environmental impacts from manufacturing, yet this frame type has far more intensive maintenance regimes in order to protect and preserve the material.

While it is indeed difficult to overcome the uncertainty of selecting a single assumed service life for an assembly without fully understanding the building context and maintenance regime, comparative LCA facilitates the exploration of this topic through the testing of multiple use scenarios. This approach recognizes that the choice of maintenance regime may vary based on geographic location, maintenance budget, or building type, and that LCA results will vary based on the selection of maintenance practice. Because comparative LCA enables comparison across the full lifespan not only with regard to materials but between maintenance practices as well, it is useful as an aide in operational decisions during the building use stage or as an additional factor in component comparison during building design.

This comparative study aims to expand discussion of the role of service life and use-stage impacts on total life cycle environmental impacts of window framing assemblies and to more accurately display the design consequences of material selection.

Description of Approach

In order to tease out the significance of use-stage decisions, such as the frequency of maintenance, repair, and replacement cycles, this comparative LCA examines aluminium, wood, aluminium-clad wood and PVCu windows using three different use scenarios associated with different maintenance regimes. The comparison of multiple service life assumptions gives a range of results for each material assembly, effectively providing a realistic basis for comparison of material durability despite the uncertainty associated with assuming a single potential service life.

Use scenarios were run by separating initial material inputs from additional materials associated with maintenance, repair, and full frame replacement. The model uses an incremental allocation methodology to account for periodic component replacements associated with failure and wear rather than a pre-emptive, timed replacement of whole frames across a building. This methodology estimates the usual cycles of repair and maintenance of individual components of the window framing assemblies on a percentage basis rather than assuming a complete assembly replacement, as the components of a window require maintenance and replacement at different rates based on the model assumptions of maintenance and repair. For example, if the weather stripping or opening hardware on a given window in a school or office building becomes worn out, it is far more likely that the particular component will be replaced or fixed, rather than prompting the replacement of every window in the building. Incremental allocation therefore acts as an averaging out of maintenance activity across multiple windows and allows for common estimating practices, such as: after a certain period of time, 2% of windows will require hardware replacement in any given year.

Additionally, allocation of environmental burdens to each component allows for the model to approximate realistic system behaviour for the specific maintenance scenario by considering incremental maintenance requirements based on the physical relationships between components. This methodology is consistent with an approach to maintenance scenarios that maintains functional equivalence across assembly types and practices based on consistent window performance throughout the full building life cycle.

Replacement Rates and End-of-Life Modelling

Useful life and replacement cycles for components and full assemblies are difficult to pin down for building materials, as numerous factors lead to the replacement, recycling, or disposal of window assemblies and their sub-components. In addition to inherent material qualities and specific approaches for design and detailing, a multitude of additional factors–from building type and ownership to economics, aesthetics and natural disasters–can result in assemblies being discarded much earlier or far later than their originally expected lifespan. For more detailed case studies on aluminium disposal, refer to Report Two of this series, *Aluminium Recyclability and Recycling*.

In order to test quantitatively the significance of durability in the full life cycle of window framing, three use scenarios were developed that seek to represent a range of potentials grounded in the material attributes and typical maintenance practices for each

	SCENARIO 1: GUARANTEE (little to no maintenance)	SCENARIO 2 (low maintenance, shorter life)	SCENARIO 3 (high maintenance, longer life)
Anodised Aluminium	25 yrs. : Full frame replacement	No cleaning of frames 20 yrs. : Replace weather sealing 2%/yr: Replace hardware 60 yrs. : Full frame replacement	Annual cleaning of frames during window cleaning 20 yrs. : Replace weather sealing 2%/yr: Replace hardware + 80 yrs. : Full frame replacement
Painted Wood	20 yrs. : Full frame replacement	12 yrs.: Repaint when coatings have failed 15 yrs. : Replace weather sealing 2%/yr: Replace hardware 30 yrs. : Full frame replacement	8 yrs.: Repaint and treat wood on regular basis to prevent failure 15 yrs. : Replace weather sealing 2%/yr: Replace hardware + 80 yrs. : Full frame replacement
Aluminium-Clad Wood	20 yrs. : Full frame replacement	No refinishing 15 yrs. : Replace weather sealing 2%/yr: Replace hardware 30 yrs. : Full frame replacement	*Not viable due to inability to protect wood through additional maintenance.*
PVCu	20 yrs. : Full frame replacement	No refinishing 15 yrs. : Replace weather sealing 2%/yr: Replace hardware 30 yrs. : Full frame replacement	*Not viable due to inability to prolong life span of primary material.*

Fig 5.2 Maintenance activities for aluminium, wood, aluminium-clad wood, and PVCu window frames

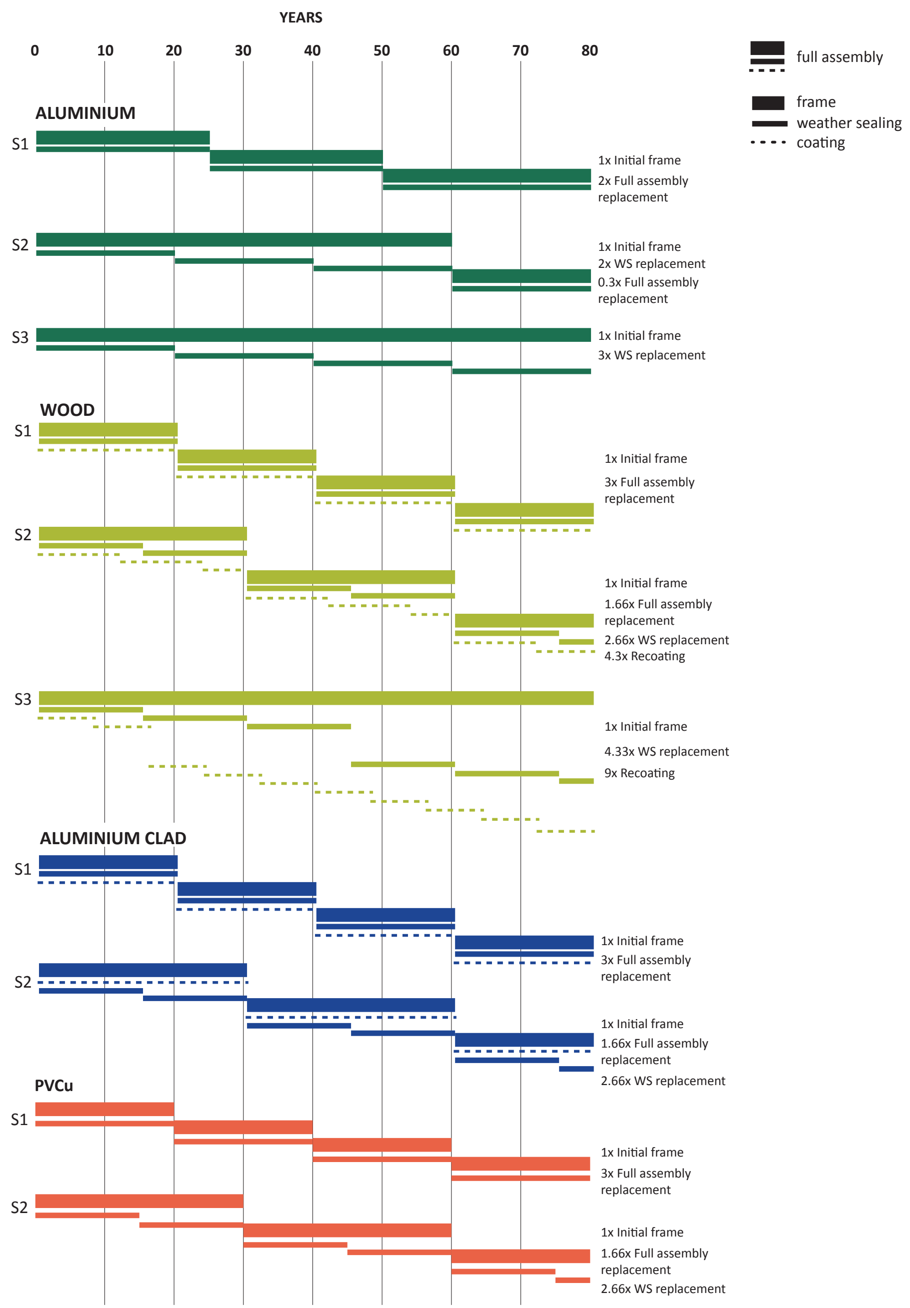


Fig 5.3 Replacement cycles for window frame components over building lifetime per scenario

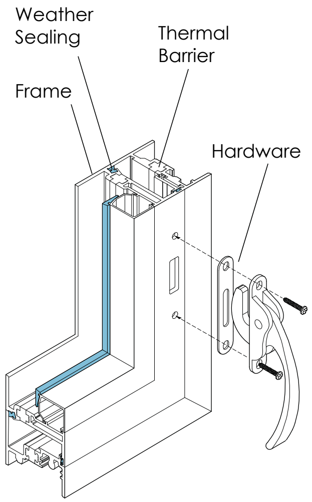


Fig 5.4 Thermally broken aluminium window framing assembly components

window frame assembly. The goal of these scenarios is not to find the correct service life of a window, but rather to demonstrate the range of full life cycle impacts based on realistic use-stage assumptions (RSMeans 2012).

Scenario 1 represents the most conservative estimate of window life; it assumes that no significant repair or replacement activities are conducted and that the entire frame assembly is disposed of or recycled and replaced at the end of a typical manufacturer guarantee. As there is presently little consensus on true service lives for architectural products, guarantees are commonly used in published comparative LCAs of window frames, even though they do not represent a realistic portrayal of in-situ circumstance.

Scenario 2 describes a basic maintenance regime in which a typical building manager or owner follows commonly prescribed maintenance practices aimed at reaching a longer life span for the window while maintaining a high level of window performance. Depending on the frame type, maintenance practices, see Figure 5.3, may include periodic replacement of damaged or worn components or hardware at regular intervals, and refinishing of the framing material. Scenario 2 matches the use stage assumptions that were used in Case Study 1 (Chapter Four).

Scenario 3 describes a high-maintenance regime in which a building manager or owner follows best practices aimed at extending the lifespan of a high-quality window through regular and frequent maintenance practices. For wood assemblies, this includes regular recoating and refinishing of frames, while for aluminium, maintenance includes annual cleaning of the external frames. The use scenario also considers regular replacement and repair of hardware, weather stripping, or sealants as would be expected over time per assembly type to maintain thermal and moisture performance.

All assemblies are modelled using end-of-life disposal scenarios tuned to present construction and demolition waste diversion and recycling rates. Aluminium, steel, paper and plastics receive credits associated with materials diverted from the waste stream and recycled at end of life, while wood products receive credit from energy recovery associated with incineration. End-of-life scenarios have been adjusted from those used in the previous study to account for the initial material inputs of additional materials used for maintenance of parts and components during the use stage. End-of-life modelling utilises the End-of-Life Recycling Method as recommended by ISO standards and the ILCD Handbook (ILCD 2010, ISO:21930 2006) and described in Chapter Four.

Results

The results of the LCA model clearly indicate that there are significant differences between the embodied environmental impacts of window framing materials, even in the base case. Additionally, the large variation between results across use scenarios within each frame type also indicates that both the durability and useable life assumed for window framing assemblies are significant, and should be the subject of further research. For aluminium window framing, the differences between use scenarios are striking. Between the most conservative aluminium framing scenario (S1), which takes the guarantee period as an estimate of useable life, and the least conservative scenario (S3), there was a 52% decrease in the calculated global warming potential and a 45% decrease in calculated fossil fuel depletion, indicating that studies that utilize guarantee periods as a means of estimating service life may be more than doubling their estimate of global warming potential and other impacts for this product.

For other assemblies, like wood window framing, variations in durability of frame material (or shorter replacement cycles) were not as significant. For example, between scenario 1, with full replacement of the all-wood window frame after 20 years, and scenario 3, in which the frame lasted for the full 80-year life cycle of the building, there was only a 13% difference between assessments of global warming potential and a 9% increase in eutrophication impacts for wooden window framing. This reveals that a high proportion of such impacts is tied to maintenance activities such as painting and refinishing rather than the initial manufacturing, production or disposal of the base materials. While these environmental savings of increased maintenance may seem small, there are also economic and labour savings that support the higher maintenance regime.

Other framing assemblies, such as PVCu, however, do not benefit as clearly from increased maintenance activity over long time frames due to the relative instability of the base material and conventional detailing - making high durability scenarios unfeasible.

Aluminium-clad wood framing is similarly challenged from a long-life perspective, as the composite nature of the assembly poses difficulties for durability. Present data for typical frames do not support expected lifespans of greater than 30-40 years, as the design and detailing of such windows prevents maintenance regimes that actively preserve the wood base, such as retreating or recoating wood, as one would with solid wood window assemblies. While the end-of-life disposal scenario assumes that metal cladding could be stripped from wooden frames and recycled at a typical diversion rate for aluminium building products, much of the impacts from the full assembly are tied to the manufacturing of the wooden frame and additional co-products, all of which would be sent to landfill or incineration upon disposal, yielding higher environmental impacts than for the aluminium framing assembly.

Analysis of impacts by life cycle stages reveals differences in the role of primary frame material - aluminium, wood, aluminium-clad wood or PVCu, relative to necessary co-products associated with sealing, coating, weather proofing and hardware, which may be replaced at faster rates during the full life of the building.

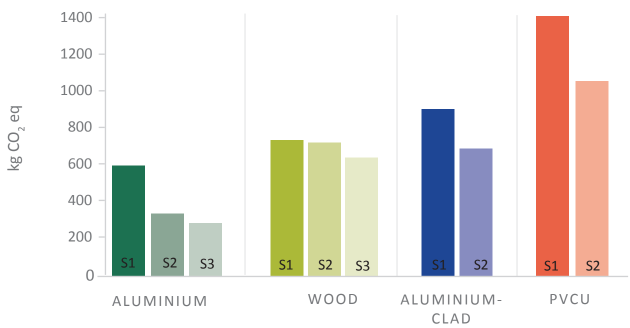
While the end-of-life scenarios used in the model consider material recovery, including diversion of demolition material from landfills for either recycling or incineration, not all materials benefit equally from recycling in assessments of embodied environmental impacts. Aluminium, with its high recovery rates, robust scrap market and efficient recycling mechanism, receives significant credits in LCA calculations using the End-of-Life Method, which awards credits to the assembly studied for reducing the pressure for primary aluminium in future products. Since metals such as aluminium can easily be recycled for use in new products, the end-of-life approach rewards products not for their recycled content, but for their recyclability at end of life, emphasizing the cyclical nature of such materials. Material losses and burdens associated with recycling activity are included in the model assessment.

PVCu windows receive some credits at end of life, but the credits are very small when compared to manufacturing stage impacts. Current low recycling rates for plastics, coupled with potential material integrity loss in recycling, make PVCu window framing a less attractive option, though increase in waste diversion and material reclamation for plastics in construction would decrease their relative impacts.

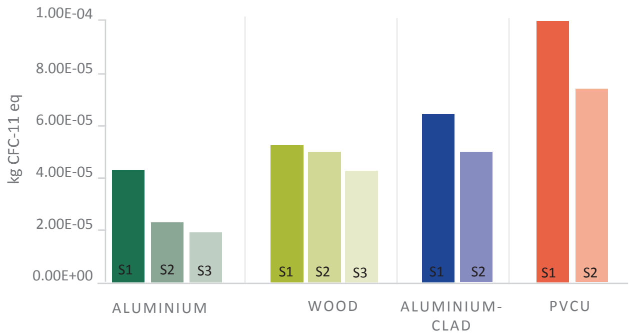
Scenario 1: Guaranteed Service Life
Scenario 2: Basic Maintenance
Scenario 3: High Maintenance

Fig 5.5 LCA results for each of the window assemblies and use scenarios across TRACI 2.1 impact categories. Scenario 3 was not a viable option for Clad Wood or PVC, and is therefore not represented

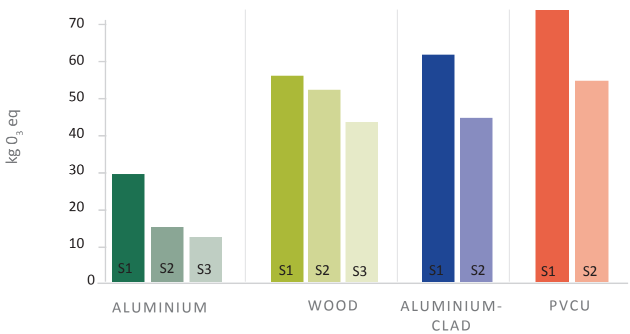
Global Warming Potential



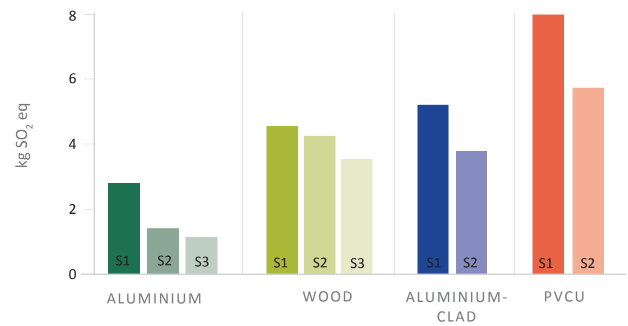
Ozone Depletion



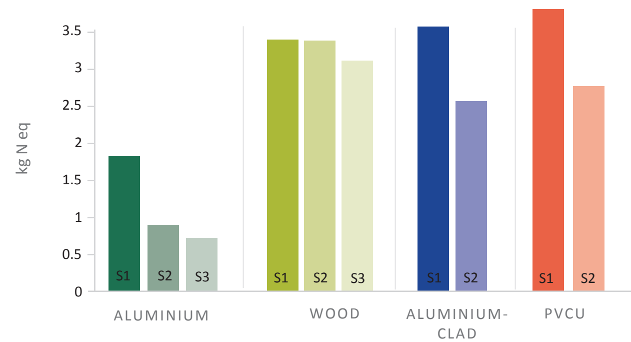
Smog Formation



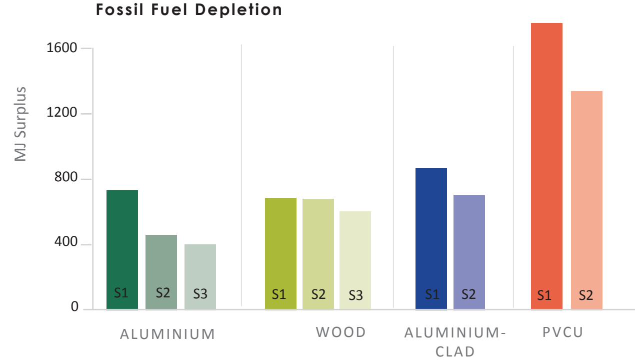
Acidification



Eutrophication



Fossil Fuel Depletion



Discussion

Results of the Life Cycle Assessment have shown the full cradle-to-grave impacts of aluminium window framing to be far less than previously reported by other studies. When the lifespan of aluminium products are considered across the building's life, the global warming potential of a moderately maintained aluminium window assembly is 68% less than PVC and 50% less than the best case scenario for aluminium-clad wood. Well maintained wood windows were found to have a 7% lower impact from a carbon perspective than the long-life scenario for aluminium-clad wood framing, and to have a nearly 30% lower impact than aluminium-clad wood windows when the manufacturer guarantee period is used as an estimation of actual life cycle. However, when considering fossil fuel depletion impacts, moderately and well maintained aluminium windows (scenarios 2 and 3) required less energy to produce and maintain over their lifetime than any of the wood scenarios.

Well maintained aluminium window framing proved to be the least impactful option across all categories, in large part due to the credits delivered at end of life from recycling aluminium into future building products. Therefore, while this model was initially built to measure the importance of durability and maintenance in the use stage of the life cycle, it has become clear that material reclamation and recycling at end of life is the most significant contributor to reducing the embodied environmental burdens of window framing products.

Admittedly, not all materials and assemblies are affected equally. Aluminium window frames in particular are adversely affected when life cycles stages are simplified or assessment periods are shortened to exclude the benefits associated with durability, low maintenance requirements or end of life (EAA 2013). The very attributes that contribute to the relatively high impacts of initial frame production cited in several existing studies (Sinha & Kutnar 2012, Asif et al. 2007, Lawson 1995) contribute to decreased impacts incurred during the product life cycle. Just as a first-cost model can hide long-term costs incurred by maintenance and replacement, LCAs that ignore the use stage or focus on recycled content rather than robust end of life modelling may unintentionally misrepresent the full environmental impacts of products.

	Aluminium			PVCu		Aluminium/wood		Wood		
	S1	S2	S3	S1	S2	S1	S2	S1	S2	S3
Global Warming (Kg CO_2 Eq)	5.99E+02	3.38E+02	2.87E+02	1.42E+03	1.06E+03	9.12E+02	6.95E+02	7.41E+02	7.29E+02	6.46E+02
Ozone Depletion (Kg CFC-11 Eq)	4.30E-05	2.30E-05	1.92E-05	1.00E-04	7.43E-05	6.45E-05	4.68E-05	5.27E-05	5.01E-05	4.28E-05
Smog (Kg O_3 Eq)	2.87E+01	1.47E+01	1.20E+01	7.26E+01	5.37E+01	6.07E+01	4.38E+01	5.50E+01	5.13E+01	4.26E+01
Acidification (Kg SO_2 Eq)	2.80E+00	1.41E+00	1.15E+00	7.96E+00	5.72E+00	5.20E+00	3.77E+00	4.54E+00	4.25E+00	3.52E+00
Eutrophication (Kg N Eq)	1.71E+00	8.41E-01	6.80E-01	3.82E+00	2.77E+00	3.34E+00	2.41E+00	2.92E+00	3.17E+00	3.18E+00
Fossil Fuel Depletion (MJ Surplus)	7.34E+02	4.60E+02	4.03E+02	1.76E+03	1.34E+03	8.67E+02	7.07E+02	6.87E+02	6.82E+02	6.04E+02

Fig 5.6 LCA results for each of the window assemblies and use scenarios across TRACI 2.1 impact categories. Model results are for 1 m2 of window framing over an 80-year building life span, inclusive of materials manufacturing, use (replacement and maintenence), and end of life

Accurate and definitive predictions of durability are challenging and rely on a range of context and design specific factors, some of which are explored in Report One of this series, Aluminium and Durability. Local climate, installation quality, architectural detailing, occupant behaviour and owner expectations can have significant effects on the actual lifespan of a product or assembly when installed in a real building. While increased data on realised product lifespans will help in creating more grounded estimates, project-specific factors will always drive individual cases, making it difficult to clearly and consistently identify a typical building for use in modelling. In light of this uncertainty, use scenarios provide a means of testing our assumptions and understanding the relevance of factors such as durability.

SIX

modelling manufacturing

Modelling Manufacturing

How does variability in the production of aluminium used in building products and assemblies affect estimates of life cycle environmental impacts? Which manufacturing processes contribute the most to environmental impacts of aluminium products? Within those processes, what is the variability and the source of such variability?

Variability in Manufacturing

The primary aluminium value chain begins with bauxite mining followed by refining of bauxite to produce alumina, then the energy-intensive electrolytic reduction of alumina into liquid aluminium, followed by ingot casting and shaping through rolling or extrusion into semi-finished and finished products. In the case of aluminium window framing assemblies, a cast aluminium billet is extruded to produce profiles. These profiles (or extrusions) are then cut, joined with other aluminium and non-aluminium components, formed and finished as final products. Each of the processes for creating the finished product transforms energy and consumes resources, but smelting dominates this energy and resource requirement, indicating that sustainability efforts should focus on this portion of the supply chain (albeit that no subsequent processing can occur without the smelting process).

As discussed in previous chapters of this report, the smelting of aluminium is an energy intensive activity. However, there is also variability between individual plants and regions in which aluminium is produced. Within the manufacturing and production of aluminium products, the largest sources of variability from plant to plant are the power source of the electricity used and the energy intensity of the electrolytic process (Liu and Müller 2012). The latter can be attributed to global technology and efficiency variations, which are broadly a function of age of operations. Although the variation in energy intensity has straightforward implications for environmental impact, the impacts from the change in power mix are less evident. In many cases, the power source utilized is geographically dependent on availability, and the power used may be based on a mix of hydropower, gas, or coal-fired power generation, if grid-based.

Given that recycling of aluminium requires only 5% of the process energy of the primary material (IAI 2009), sustainability efforts may also focus on increasing the reclamation rate at the end of useful product life. The recycling rate for aluminium in building products is an especially difficult variable to study, in particular because of a lack of hard data on local practices for reclamation, which vary from project to project and region to region based on societal commitment and processing technologies available (Liu and Müller 2012). For data on specific case studies exploring rates of recycling and reclamation, see Report Two of this series, *Aluminium: Recyclability and Recycling*.

The global average collection rate for aluminium from construction and demolition (C&D) disposal streams is estimated to be 86%, with Western Europe averaging 95%, China 92%, and North America 80% (IAI 2014).

While such recycling rates are relatively high, a function of the value of aluminium scarp and its massive uses in the built environment, the availability of scrap is limited by the fact that such uses have long lifetimes and so the aluminium currently available for recycling reflects what went into the built environment 20, 30, 50 or 100 years ago. Thus, when discussing the viability of utilizing high recycled content aluminium, it is important to consider the quality of available scrap and its geographic location, given that mature markets are likely to have the most available scrap while requiring fewer inputs than newly built cities, such as those in China or the Middle East.

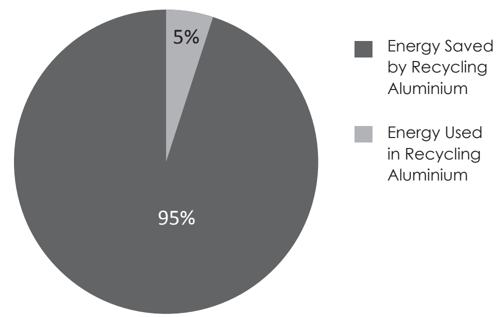


Fig 6.1 Energy use for production of primary aluminium compared to the production of recycled aluminium (data based on IAI 2009)

Almost 300 million tonnes of aluminium are currently in productive use in buildings (IAI 2014), but this aluminium is not distributed evenly across the globe. For example, Western Europe has historically benefited from a larger volume of aluminium stored in use and therefore creating a flow of high-quality scrap available for recycling, while regions with newer urban development are not able to draw from the same historical stocks of scrap. For example, Europe has an estimated 160 kilotonnes of aluminium in use (in all products) and recycled more than 3 kilotonnes of post consumer scrap in 2013 (up from 1.6 kilotonnes in 2000) (IAI 2014b, unpublished). By comparison, South America has only 25 kilotonnes in use and collected less than one kilotonne in 2013 (IAI 2014d, unpublished).

However, developing countries are catching up in terms of in-use stocks, as large populations increase their per capita consumption of aluminium. For example, China now has close to 190 kilotonnes of aluminium in use due to its recent construction boom, and has significantly more old scrap available now (about 2 kilotonnes in 2013) than just fifteen years ago (approximately 500 thousand tonnes in 2000) (IAI 2014c).

Additionally, the aluminium collection rates from C&D disposal streams seem to have improved, along with the influx of available scrap, increasing from an estimated 80% in 2000 to 92% in 2013 (IAI 2014, unpublished), according to expert opinion. This trend is reflected globally: as the quantities of aluminium scrap increase and the infrastructure and markets to support this activity improve, so do recycling rates.

Previous LCA studies on the topic of environmental impacts from aluminium production have generally focused on particular processes within the life cycle, such as smelting (Norgate and Rankin 2001; Ootani et al. 2002; Tharumarajah 2008), or they have focused on specific environmental impacts, such as the production of perfluorocarbons (IAI 2013b) or greenhouse gas emissions (Norgate et al. 2007). Those taking a broader perspective on environmental impacts of the production supply chain have tended toward geographic specificity in order to avoid the uncertainty associated with the geographic variations in production discussed above and to position positively regional production centres by studying primarily Europe, U.S., and Australia (Tan and Khoo 2005; Norgate et al. 2007), which together accounted for less than fifteen percent of global aluminium production in 2013 (USGS 2015).

Fig 6.2 Coal fired power station in Mehrum, Germany

The choice of power mix when conducting a Life Cycle Assessment is a controversial decision (Koch and Harnisch, 2002), generally leading LCA practitioners to default to using the annual regional **grid mix** or industry-specific averages provided by the IAI annual publications (IAI 2015b). This data source is also used for LCA practitioners doing attributional or consequential LCAs across space and through time. However, this generic substitute fails to capture the complexity of the system, and may lead to an over or underestimate of environmental impacts, as many aluminium smelters have their own specific power mix. This is particularly true in locations that have access to hydropower, self-generating energy capacity, or are co-located with power plants, where the use of average surveyed power mixes has been shown to introduce a high degree of uncertainty and inaccuracy for specific products (da Silva et al. 2010).

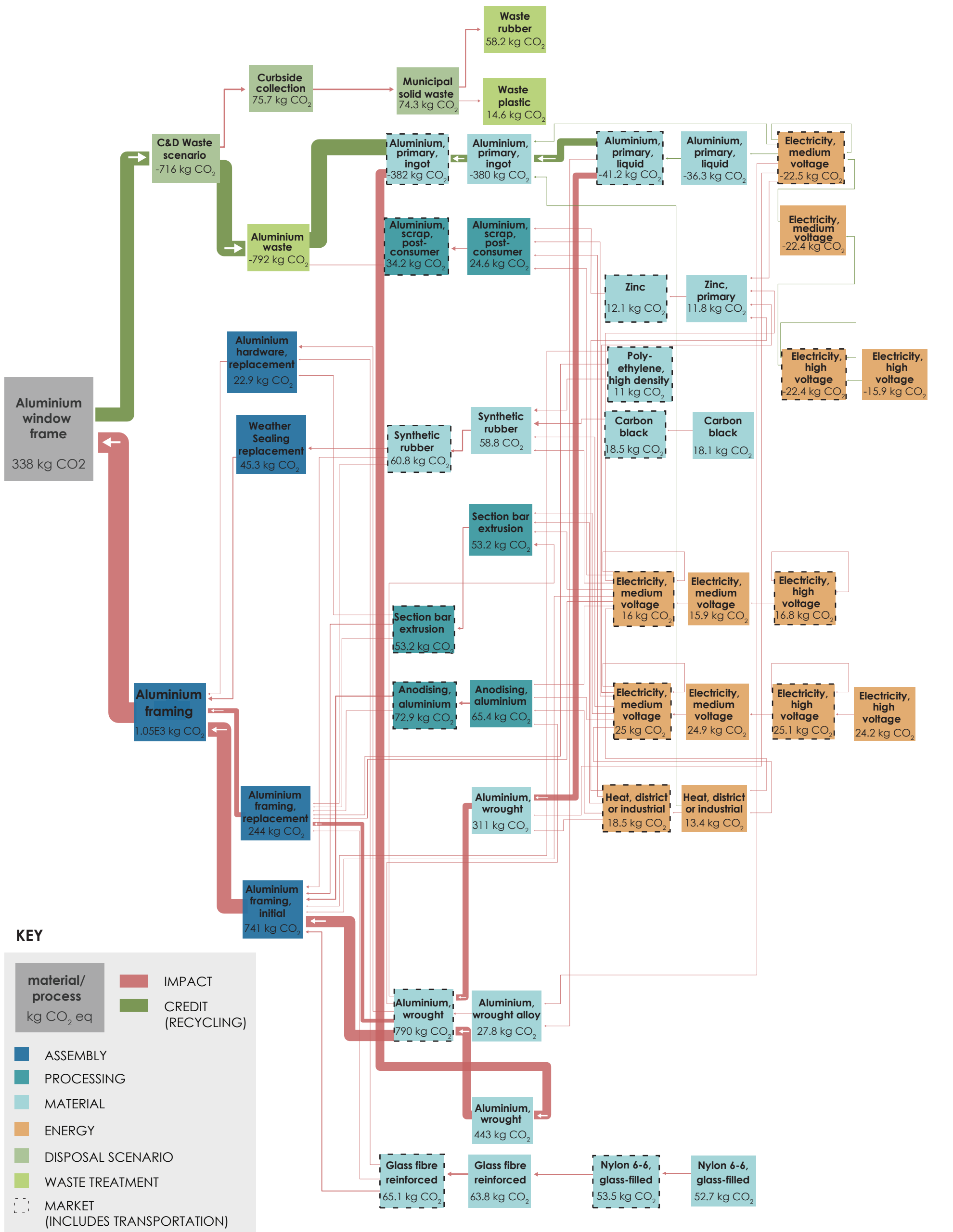


Fig 6.3 Contributions to overall Global Warming Potential in the lifecycle of aluminium (Diagram based on SimaPro network diagram, PRé Consultants)

Description of Approach

The comparative LCA models presented in this chapter further narrow the scope of the previous two case studies to examine the impacts of the primary variables of the manufacturing and disposal processes specific to aluminium. To this end, each model limits the scope to a single aluminium window frame assembly so that the variables specific to aluminium processing can be directly compared between the scenarios, and their significance can be isolated. The technique of sensitivity analysis is used to compare the relative impact of the manipulation of two of the variables associated with the production and end of life of aluminium.

Power Sources and End-of-Life Variability

This set of comparative LCA models uses sensitivity analysis to test the importance of reclamation rates and the power mix for smelting to the overall environmental impacts of aluminium.

This mode of analysis uses the **one-at-a-time [OAT] technique** for sensitivity analysis to understand the importance of each of the two parameters on either end of the life cycle with regard to overall aluminium assembly environmental impacts. This allows for a better understanding of where the most productive efforts can be focused to make the life cycle more sustainable. The OAT approach is suggested when investigating local sensitivity analysis for particular variables and parameters that are assumed to be uncorrelated (Groen 2014) and may be used on small assembly systems. It requires selection of a subset of parameters or processes within an assembly to manipulate within a selected range in order to see how much influence the manipulation has on the result.

Model 1: Energy Mix tests the sensitivity of the model to the power source for smelting. A 1% cut-off by impact was used to draw a study boundary around the processes considered. Because of the difference in magnitude of impacts for primary and recycled aluminium, this cut-off excludes manipulation of the power sources for any recycled material processing.

The model is manipulated by changing the power mix from the previous studies, which used a global aluminium industry average mix, to single-input power sources. It tests the three most commonly used power sources for aluminium processes: hydropower, natural gas, and coal, which uses an 80% hard coal to 20% lignite mix based on the aluminium industry global average (Weidema 2013).

Although in reality grid-powered aluminium smelters often use a mix of power sources, the following model uses single sources of power in order to clarify the contrast between the scenarios.

While thermal energy sources in aluminium production processes also vary according to geography, thermal energy is not manipulated in this study for reasons of clarity and materiality. While smelting electricity contributes 70% of the energy requirement of global primary aluminium production (mining to casting), direct thermal energy contributes less than 20%; the remainder is made up of transport energy and the energy required for ancillary material production (IAI 2014).

Model 2: Recycling examines the importance of end-of-life assumptions, using three aluminium recycling and reclamation rates for projects: 80%, 90%, and 95%. As this change is made to the model, the percentage of overall impact is examined to see if the change in the recycling rate results in the expected linear change to each of the environmental impacts. For this model, the global aluminium industry average power mix from the previous chapters is used.

End-of-life modelling in each instance utilizes the End-of-Life Recycling Method as recommended by ISO standards and the ILCD Handbook (ILCD 2010, ISO:21930 2006) and described in Scenario 2 in Chapter Four. In order to test these parameters under common practice, this model assumes the use stage maintenance of Scenario 2 in Chapter Five: a basic maintenance regime in which a typical building manager or owner follows commonly prescribed maintenance practices aimed at reaching a longer lifespan for the window while maintaining a high level of window performance. The details of the aluminium framing assembly are described in Chapter Three.

The credits for recycling in this chapter assume that the material re-enters the production stream in the global market. This is particularly important in Model 1, as the recycling credit assumes the avoided primary material would have been produced using the global average energy mix, rather than the energy mix used in the production of the modelled product.

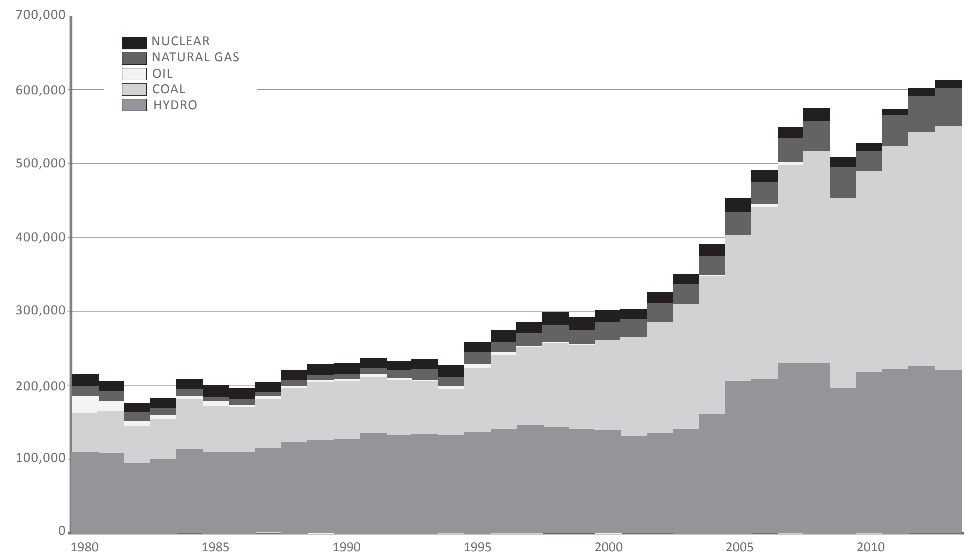


Fig 6.4 World primary aluminium smelting power mix, 1980-2013 (data based on IAI 2014a)

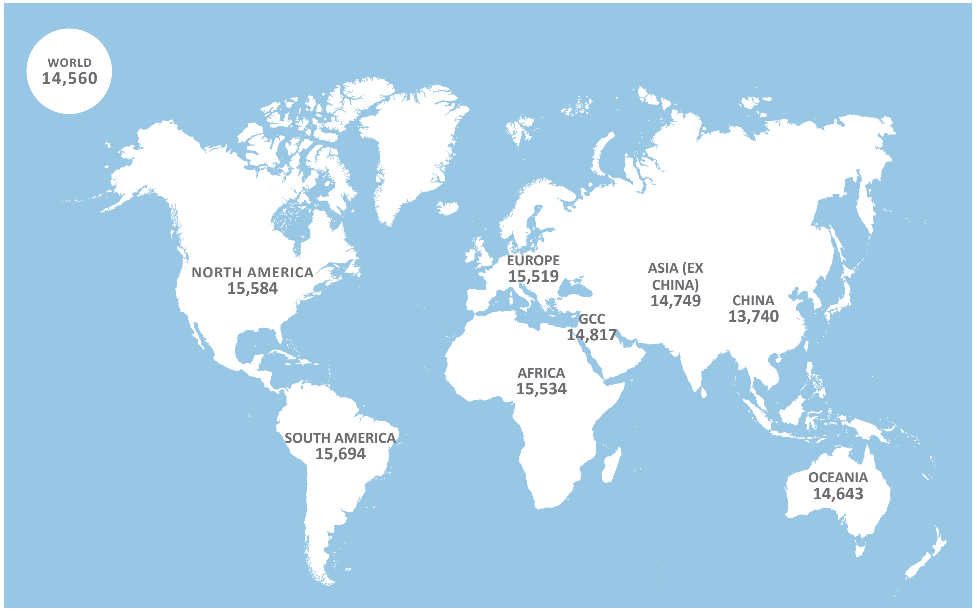


Fig 6.5 World primary aluminium smelting energy intensity, in kilowatt hours per tonne of aluminium (data based on IAI 2014a)

Results

As expected for the power mix variation test described in **Model 1: Energy Mix**, the selection of power source has a large effect across all impact categories. The dramatic differences in environmental impacts across the options show that selection of power source for smelting is the action with the most environmental impact in the aluminium life cycle. Hydropower, as the only renewable energy option tested, yields by far the best results for an energy source in all measures of environmental impact, even providing a net credit for avoided impacts in all categories except ozone and fossil fuel depletion.

The results do not indicate a clear second-best power source from the scenarios examined. Current global focus on climate change indicates that an increase in the use of natural gas would be preferable over scenarios using coal, as natural gas contributes only 42% of the global warming potential of coal. However, while natural gas also has excellent performance in the smog formation, acidification, and eutrophication categories, providing a net environmental benefit for each, it has significantly worse impacts in the areas of ozone depletion (five times greater than coal) and fossil fuel depletion (four times more than coal). Coal is the only energy source option that has zero categories for which it provides environmental benefits, and it is the worst option with regards to carbon emissions, smog formation, acidification, and eutrophication.

In each case presented in Model 1, the performance of the global average is rarely accurate for any single power source, as it reflects an industry average mix. As hydropower is used extensively in certain areas of the world but not at all in others, its inclusion in the industrial global average energy mix reduces the apparent impacts of aluminium in many LCAs, as the default in LCA practice is to use the global mix. Similarly, using a global average fuel mix as proxy for a mix dominated by either hydropower, natural gas, or a combination thereof will underreport the benefits of aluminium, as the global average mix is dominated by coal as a fuel source. As coal is the only fuel source that has a significant harmful impact in the areas of smog formation, acidification, and eutrophication, the use of the global average will fail to reflect the environmental benefits in those categories associated with the use of the other fuel sources. Ideally, when analysing the relative impacts of power mixes and manufacturing locations, it would be more appropriate for designers attempting to evaluate climate impacts of aluminium

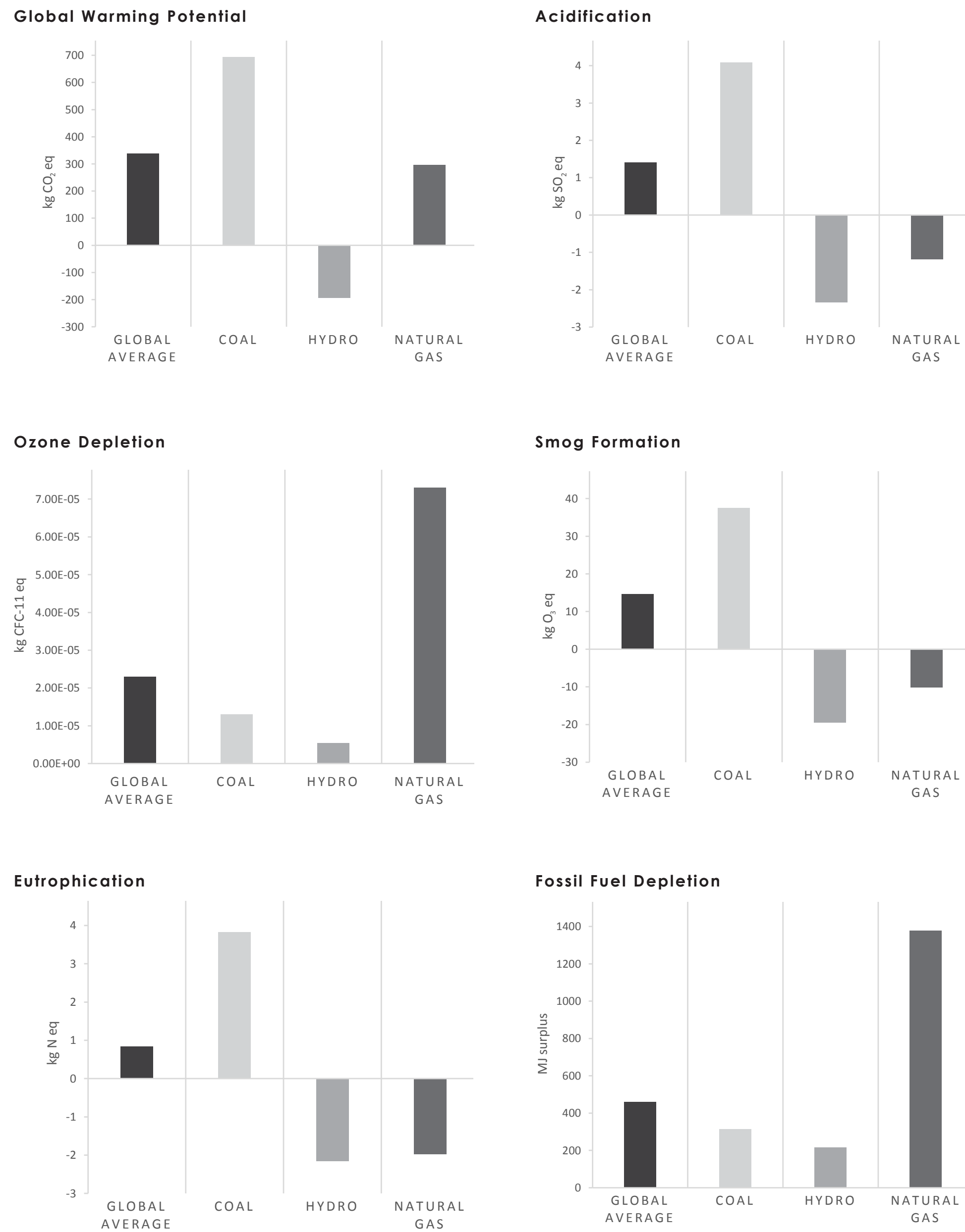


Fig 6.6 LCA results for each of the energy source scenarios in Model 1 across TRACI 2.1 impact categories. Negative values are possible because recycling credit assumes the avoided primary material would have been produced using the global average energy mix.

to use manufacturer- and location- specific data for products they are using, such as that provided in Environmental Product Declarations (EPDs), discussed later in this chapter.

In **Model 2: Recycling**, it is clear that while increased recycling rates will have a direct improvement on environmental impacts, the relationship is not always linear, and there is a reduction in the rate of returns as the recycling rate increases in most categories. For global warming potential, acidification, and eutrophication, the relationship between the percentage change in recycling rate is linearly reflected in the results, with a standard nine-tenths of a percent change for every percent increase in recycling rate. This relationship is very similar to that shown in smog formation potential, which only begins to see a small decrease in returns between the 90% and 95% recycling rate from the standard nine-tenths of a percent for each one percent increase. This indicates that there will be a continued decreasing rate of returns as the recycling rate exceeds 95%, but additional study would be necessary to determine the rate of falloff.

The relationship between recycling rate and decrease in ozone depletion potential is also linear, but the effect is less strong: a ten percent change in the recycling rate only leads to a seven percent change in the ozone depletion impacts.

Fossil fuel depletion is the impact category least affected by a change in recycling rate. The relationship is linear, but each change in recycling rate by ten percent only yields a decrease of fossil fuel impacts by six percent. This is most likely due to the impacts associated with the recycling process itself, which requires the use of thermal energy in order to process the reclaimed material.

Fig 6.7 Collected aluminium scrap

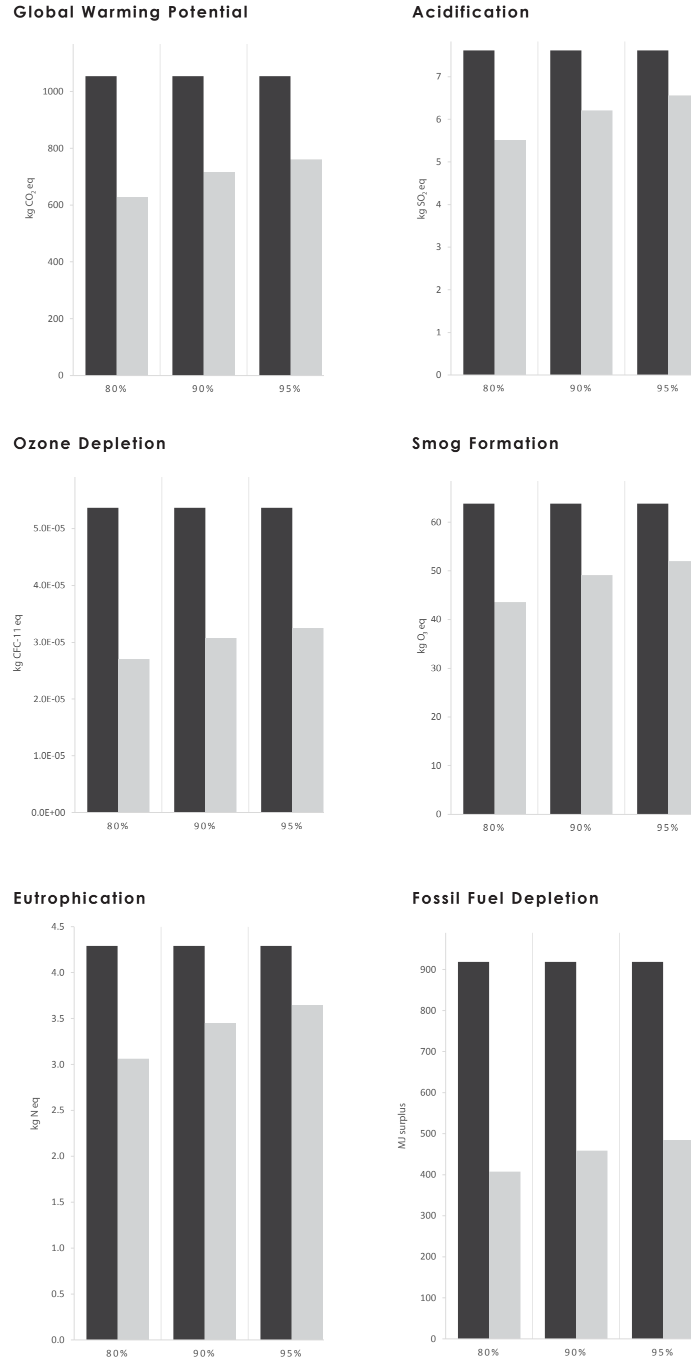


Fig 6.8 LCA results for each of the scenarios in Model 2 across TRACI 2.1 impact categories

Discussion

The results of these models demonstrate the importance of the decisions made at both the start and end of life for aluminium building products. The dominance of the choice of power source during the smelting process on environmental impacts indicates that the power mix used in production prior to arrival of the aluminium building product at a construction site is the most significant indicator of environmental impacts of the product. In practice, this is directly related to the location from which the aluminium is sourced. The demonstration of a significant linear impact of reclamation rates on environmental impacts also emphasizes the importance of recycling to improving environmental performance of aluminium building products.

Although design decisions are not directly related to the selection of a power source for the smelting process, and global drivers of location of smelting capacity will not be greatly influenced by the design community, designers may implement the lessons learned from the scenarios presented in Model 1: Energy mix through an incorporation of EPDs in the specification writing process. EPDs report independently verified LCA results in a standardized manner, allowing for direct comparison across products. As the choice of power source is such a major driver of environmental impacts for aluminium, this choice is reflected in the impacts shown in an EPD. Specifying a maximum allowable impact for an aluminium product using an environmental performance specification for aluminium products that can be verified using EPD information would likely result in the selection of aluminium products manufactured using cleaner fuel sources.

On the other hand, designers have the ability to immediately incorporate the lessons shown in Model 2: Recycling directly into the design process. The strong linear relationship between recycling rates and reduction in environmental impacts implies that designing for the highest possible degree of aluminium material reclamation is not only beneficial from an economic standpoint (because of the high value of scrap), but also from an environmental standpoint, as each impact category experiences significant reductions for each additional percent of aluminium reclaimed. In design, implementing a high recycling rate requires a life cycle mentality that not only considers how assemblies are put together, but also how they may be efficiently taken apart after they are no longer of use. This mentality is demonstrated in Design for Deconstruction, which is discussed in Report Two of this series.

The degree of importance associated with recycling implied by the model indicates that deconstruction of existing building stock should be done with careful attention paid to scrap metals. Not only will this help increase the amount of aluminium available as recycled content for future aluminium use, it will also prevent future impacts of the demand for additional primary material, which is shown in Model 1 to be the most energy-intensive and impactful stage of life for aluminium building components.

Fig 6.9 A coal fired power station in Datteln, Germany

SEVEN

interim conclusion

Interim Conclusion

Life Cycle Assessment is a powerful methodology that provides a scientific basis for comparing the environmental impacts of materials and processes. It renders intelligible the intertwined and layered flows of materials and energy over space and time, allowing designers to move towards a quantifiable basis for making decisions regarding environmental impact and performance.

LCA is also a complicated science, replete with confusing terminology, complex datasets and methodological snares. While general life cycle thinking is a comfortable fit for designers who think deeply about materials and their applications, the use of LCA in design practice is relatively new. Few designers or engineers are trained in the practice, and the industry is still in the process of developing much needed standards to guide modelling practice and interpretation.

The ultimate goal of this report is to foster discourse around the quantification of the benefits of aluminium by establishing a common knowledge base. Chapters 1-3 instruct this audience in the core concepts of LCA and some of the essential topics relating to the use of LCA for the assessment of building products. The carefully curated LCA models presented in Chapters 4-6 provide a framework for interrogation of the building product system. These LCAs emphasize the environmental impacts related to different stages of product life and point to possible actions to reduce those impacts associated with buildings and the built environment.

LCA, like any predictive modelling practice that projects behaviour decades into the future, will always have to deal with uncertainty and assumptions. For this reason, it is important to pair comparative models with real life case studies, such as those presented in Report One and Two of this project. Just as a case study may ground an abstract or idealized model, so too does the rigor of data collection used in modelled averages allow for the one-off nature of a single building to be extrapolated to larger trends and findings.

The research presented in this report underscores the conclusion that there is room for improvement across the value chain, and that quantification is an essential part of telling the story of aluminium in buildings and construction. It also shows that, at present, LCA is a useful but imperfect science, and that there are significant gaps in available data–such as geographically specific recycling rates or average realized life expectancies of common building components.

The LCA models in this report have shown that recycling rates (collection and recovery) are a driving factor in the environmental impact of aluminium building products. There is need for further research on how design and construction decisions affect collection and recovery rates in practice. Additionally, factors related to regional variation in demolition practices are not understood. Are market forces for high-value aluminium sufficient to assure optimum collection and recovery rates from buildings? Is there more that the aluminium industry and other actors along the value chain can do?

From a modelling perspective, a shift from the Recycled Content Method to an End-of-Life Recycling Method in the building and construction sector should aid in steering designers toward goals of material recovery rather than chasing after high recycled content material.

The research also highlights the importance of power source used in the smelting of aluminium as another important factor influencing the total lifetime environmental impact of products. While actual energy consumption is well studied by manufacturers, and both industry and regional averages are available, data is not often available at a resolution that easily assists product selection or differentiation at the product level. There is room for further research on sector-wide practices and reporting standards that could increase transparency regarding the energy mixes and manufacturing impacts of aluminium smelting.

As the building and construction industry deepens its understanding and use of Life Cycle Assessment, Environmental Product Declarations (EPDs) or other manufacturer-specific LCAs may aid designers in making informed decisions about material and product selection. LCA will also provide a mechanism for industry to communicate the unique attributes of their products.

frame assembly materials

Life Cycle Assessment of Window Framing: Frame Assembly Material Quantities

The following pages show the complete bill of materials for a single window frame at the end of product manufacturing for each of the basic window framing assemblies modeled (Weidema 2013).

Window frame, aluminium, U=1.6 W/m²K (GLO) | at plant

Primary Materials	Aluminium, production mix	39.7	kg
	Synthetic rubber	4.87	kg
	Reinforcing steel	0.516	kg
	Chromium steel 18/8	0.457	kg
	Polyethylene, HDPE, granulate	0.246	kg
	Isopropanol	0.0208	kg
	Acrylonitrile-butadiene-styrene copolymer, ABS	0.4	kg
	Nylon 6	0.0146	kg
	Adhesive for metals	0.29	kg
Initial Processes & Energy	Anodising, aluminium sheet	9.8	m2
	Section bar extrusion, aluminium	38	kg
	Section bar rolling, steel	0.975	kg
	Glass fibre reinforced plastic, polyamide, injection	5.27	kg
	Extrusion, plastic film	0.246	kg
	Metal working factory	2.32E-08	p
	Electricity, medium voltage, production UCTE, at grid	1.27	kWh

Window frame, wood, U=1.5 W/m²K (GLO) | at plant

Primary Materials	Sawn timber, softwood, planed, kiln dried	0.211	m3
	Sawn timber, hardwood, planed, kiln dried, u=10%	0.00171	m3
	Aluminium, production mix	3.06	kg
	Aluminium, production mix, cast alloy	0.0156	kg
	Steel, low-alloyed	5.18	kg
	Copper	0.00623	kg
	Zinc, primary	0.29	kg
	Synthetic rubber	1.14	kg
	Polyvinylchloride	0.136	kg
	Nylon 66, glass-filled	0.349	kg
	Polyethylene, LDPE, granulate	0.0233	kg
	Polypropylene, granulate	0.0233	kg
	Propylene glycol, liquid	0.000238	kg
	1-butanol, propylene hydroformylation	0.0197	kg
	Acetone, liquid	0.0173	kg
	Toluene, liquid	0.0311	kg
	Isopropanol	0.000476	kg
	Methyl ethyl ketone	0.000238	kg
	Water, completely softened	0.377	kg
	Alkyd paint, white, 60% in H2O	5.49	kg
	Benzimidazole-compounds	0.00396	kg
	Alkyd resin, long oil, 70% in white spirit	0.0244	kg
	Melamine formaldehyde resin	0.0733	kg
	White spirit	0.007	kg
	Titanium dioxide, production mix	0.000595	kg
Initial Processes & Energy	Section bar extrusion, aluminium	3.06	kg
	Section bar rolling, steel	5.18	kg
	Anodizing, aluminium sheet	0.81	m2
	Zinc coating, pieces	0.493	m2
	Metal working factory	3.67E-08	p
	Wood pellets, u=10%	-0.00444	m3
	Pellets, mixed, burned in furnace 50kW	54	MJ
	Electricity, medium voltage, production UCTE, at grid	57.7	kWh

Window frame, wood-metal, U=1.6 W/m²K (GLO) | at plant

Primary Materials	Sawn timber, softwood, planed, kiln dried	0.195	m3
	Sawn timber, hardwood, planed, kiln dried, u=10%	0.00171	m3
	Aluminium, production mix	12.2	kg
	Aluminium, production mix, cast alloy	0.0156	kg
	Steel, low-alloyed	5.12	kg
	Zinc, primary	0.29	kg
	Copper	0.00623	kg
	Synthetic rubber	2.91	kg
	1-butanol, propylene hydroformylation	0.042	kg
	Acetone, liquid	0.0136	kg
	Toluene, liquid	0.0245	kg
	Isopropanol	0.000375	kg
	Methyl ethyl ketone	0.000187	kg
	Water, completely softened	0.823	kg
	Alkyd paint, white, 60% in H2O	5.06	kg
	Nylon 66, glass-filled	1.09	kg
	Polyvinylchloride	0.136	kg
	Polyethylene, LDPE, granulate	0.0233	kg
	Polypropylene, granulate	0.0233	kg
	Propylene glycol, liquid	0.000187	kg
	Benzimidazole compounds	0.00864	kg
	Alkyd resin, long oil, 70% in white spirit	0.0244	kg
	Melamine formaldehyde resin	0.0733	kg
	White spirit	0.00551	kg
	Titanium dioxide, production mix	0.000468	kg
Initial Processes & Energy	Anodizing, aluminium sheet	3.4	m2
	Section bar extrusion, aluminium	12.2	kg
	Section bar rolling, steel	5.12	kg
	Zinc coating, pieces	0.488	m2
	Metal working factory	3.81E-08	p
	Pellets, mixed, burned in furnace 50kW	54	MJ
	Wood pellets, u=10%, at storehouse	-0.00444	m3
	Electricity, medium voltage, production UCTE, at grid	62.4	kWh

Window frame, poly vinyl chloride, U=1.6 W/m²K (GLO) | at plant

Primary Materials	Polyvinylchloride	58.4	kg
	Polyethylene, LDPE, granulate	0.00578	kg
	Polypropylene, granulate	0.219	kg
	Polystyrene, high impact, HIPS	0.208	kg
	Polystyrene foam slab	0.184	kg
	Chemicals organic	0.0287	kg
	Synthetic rubber	0.798	kg
	Aluminium, production mix	1.1	kg
	Aluminium, production mix, cast alloy	0.0174	kg
	Steel, low-alloyed	30	kg
	Copper	0.00698	kg
	Zinc, primary	0.325	kg
Initial Processes & Energy	Extrusion, plastic pipes	54.3	kg
	Injection molding, plastics	1.9	kg
	Section bar extrusion, aluminium	1.1	kg
	Section bar rolling, steel	37.9	kg
	Zinc coating, coils	2.11	m2
	Zinc coating, pieces	0.463	m2
	Metal working factory	4.32E-08	p
	Electricity, medium voltage, production UCTE, at grid	13.8	kWh

glossary

Glossary

Acidification potential is an equivalency factor of acidifying pollutants, defined by their common denominator, H^+. Example impacts caused by acidification include acid rain and acidic particulate pollution.[1]

Allocation is the partitioning of the input or output flows of a unit process to the product system under study.[2]

Avoided Burden Method is another name for the End-of-Life Recycling Method, defined below.

Cut-off factor is the specification of the amount of material or energy flow or the level of environmental significance associated with unit processes or product system to be excluded from a study.[2]

Cut-off Method is another name for the Recycled Content Method, defined below.

Embodied environmental impacts are the sum of all impacts created in the production of materials, goods, or services, and may include impacts from maintenance, or repair of the material or good.

EN15804 is the European standard for calculation methodology and reporting of Environmental Product Declarations [EPDs] for construction products or services issued by the European Committee for Standardization.[3]

Energy mix is the combination of energy resources required to produce a material, product or service; in the case of primary aluminium, the majority of energy requirement is in the form of electricity, which has been generated from a mix of primary energy sources (thermal, hydropower, etc.), but energy is also transferred through combustion of fuels (coal, gas, etc.). Energy mixes combining power and fuel mixes are often regionally defined, based on availability of energy resources.

End-of-Life Recycling Method is a methodology for treatment of recycling in LCA that is based on a product life cycle and material stewardship perspective. It considers the fate of products after their use stage and the resultant material output flows.

Environmental Product Declaration [EPD] is a highly standardized form of LCA result reporting primarily created by product manufacturers to provide environmental information about their products as a form of eco-labelling.

Eutrophication potential is an equivalency factor of eutrophying pollutants, defined by their common denominator, N. Eutrophication is associated with excessively high levels of nutrients that lead to shifts in species composition and increased biological productivity, such as algal blooms.[1]

Functional unit is the quantified performance of a product system for use as a reference unit in a Life Cycle Assessment study.[2]

Global warming potential [GWP] is an equivalency factor of greenhouse gases that enhance radiative forcing in the atmosphere, leading to climate change. The potential contribution of a substance to climate change is expressed as a ratio between the increased infrared absorption it causes and the increased infrared absorption caused by 1 kg of CO_2, and is measured in CO_2 equivalents.[1]

Grid mix is a description of the makeup and efficiency of electricity and heat transfer through a larger energy transmission system. In accordance with ISO 14044, in Life Cycle Assessment, when modelling electrical consumption, account shall be taken of the fuel mix and the efficiencies and losses associated with fuel combustion, conversion, transmission and distribution. Average grid mixes account for the temporal and spatial variability of grid efficiencies across a region, country or industry.[2]

Guarantee (or warranty) is a term of contract provided by a manufacturer and a consumer that describes protections allotted to the consumer upon purchase of a product. Such documents typically define a guarantee period or service life as a period of time over which the repair or replacement of a product is expected to be supported by its manufacturer. See *Service life* for further description.

Impact category is a class representing environmental issues of concern to which life cycle inventory analysis results may be assigned.[2]

ISO 14040/44 is the international standard for calculation methodology and reporting of Life Cycle Assessment issued by the International Organization for Standardisation.[2]

Life Cycle Assessment [LCA] is a compilation and evaluation to quantify the inputs, outputs, and potential environmental impacts of a product or service throughout its life cycle.[2]

One-at-a-time [OAT] technique for sensitivity analysis is a method of systematic procedure for estimating the effects of the choices made regarding methods and data on the outcome of a study in which one variable is changed at a time.[2]

Ozone depletion potential is an equivalency factor measuring the potential contribution of a substance to the thinning of the stratospheric ozone layer and is measured relative to CFC-11.[1]

Photochemical smog formation potential is an equivalency factor measuring secondary pollutants formed in the lower atmosphere known to cause photochemical smog, a cause of health problems and damage to vegetation. Photochemical smog formation potential is measured in O_3 equivalents.[1]

Recycled Content Method (Recycled Content Approach) looks back to where material feedstock was sourced, and provides a measure of waste diversion. This approach is based on a waste management perspective, where the general aim is to promote a market for recycled materials that is otherwise limited, uneconomic, or immature.

Recycling is the process of recovering valuable materials or resources from products at the end of their useful life, from waste streams or from production processes.

Reclamation is the process of setting aside material from the waste stream for future reuse with minimal processing.

Resource depletion (fossil fuel) is a measure of the quantity of fossil fuel resources consumed across fuel types (coal, oil or natural gas) and is commonly reported in energy values (MJ) only, without accounting for the relative scarcity or environmental impacts of individual fuel types.[1]

Service life is a period of time for which a manufacturer can be expected to be responsible for servicing or supporting the material or product. Expected service lifetimes are often a conservative estimate and are not required to represent either the maximal record life of a product or its average useable life. See *Guarantee* for further description.

Notes

1 Names and definitions of impact categories used in this report are based on TRACI2 characterization scheme, developed by the US EPA. Documentation of impact categories and characterization equations can be found at: United States Environmental Protection Agency, Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) User's Manual. 2012. http://www.epa.gov/nrmrl/std/traci/traci.html Impact categories are also well explained in Kathrina Simonen, Life Cycle Assessment, New York: Routledge, 2014.

2 ISO 14040:2006, Environmental Management - Life Cycle Assessment - Principles and Framework (ISO, 2006).

3 EN15804 - Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products.

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Towards Sustainable Cities Research Team

Michael Stacey Architects

The practice has a thoughtful approach to the design of architecture. Michael Stacey Architects' aim is to contribute to people's lives and the culture of contemporary society through an informed knowledge of humanity, study of architectural precedents and urban habitats, combined with a detailed understanding of materials and fabrication processes. This knowledge base is underscored by a long-term commitment to research. The benefit of using a component-based architecture and off-site manufacturing is that it is possible to create high-quality and cost-effective architecture delivered with the shortest possible site time. This has been demonstrated on projects at a number of scales including the Boat Pavilion, Regional Rail Stations, Cardiff Bridges and Ballingdon Bridge. The design approach of Michael Stacey Architects is based on systems of components, yet each architectural project is client and site specific

www.s4aa.co.uk

KieranTimberlake

The practice brings together the experience and talents of nearly 100 professionals of diverse backgrounds and abilities in a practice that is recognised worldwide. KieranTimberlake's projects include the programming, planning, and design of new structures as well as the conservation, renovation, and transformation of existing buildings, with special expertise in education, government, arts and culture, civic, and residential projects. KieranTimberlake seeks ways to improve the art, quality, and craft of architecture through research into new materials, processes, assemblies, and products.

http://kierantimberlake.com

Architecture and Tectonics Group of The University of Nottingham

The Architecture and Tectonics Research Group addresses the core of architecture including design as research and research that supports and stimulates the design of high quality contemporary architecture and infrastructure. Themes within this research group include: architecture as a discipline, craft, digital fabrication, form finding, offsite manufacture, façade systems, tectonics, durability, emergent materials, zero carbon architecture and human ecology.

http://www.nottingham.ac.uk/research/groups/atrg/index.aspx

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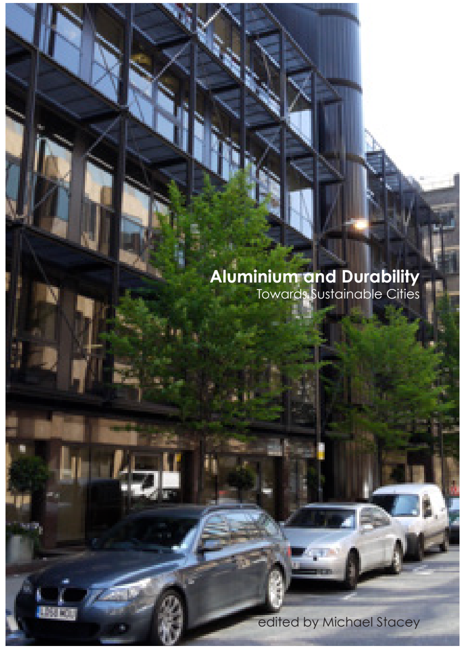
Towards Sustainable Cities: Publications



Aluminium and Durability

The durability of aluminium is probably one of the most important qualities of this metal when used to form architecture and infrastructure.

Charting one hundred years of the use of aluminium in architecture and the built environment using 50 built works from 1895 to 1986, with four historic exemplars being inspected and presented in depth.

Twelve twentieth century award winning and historically significant aluminium based buildings were inspected leading to the successful non-destructive testing of aluminium finishes on three of these projects.

Written and edited by Michael Stacey.

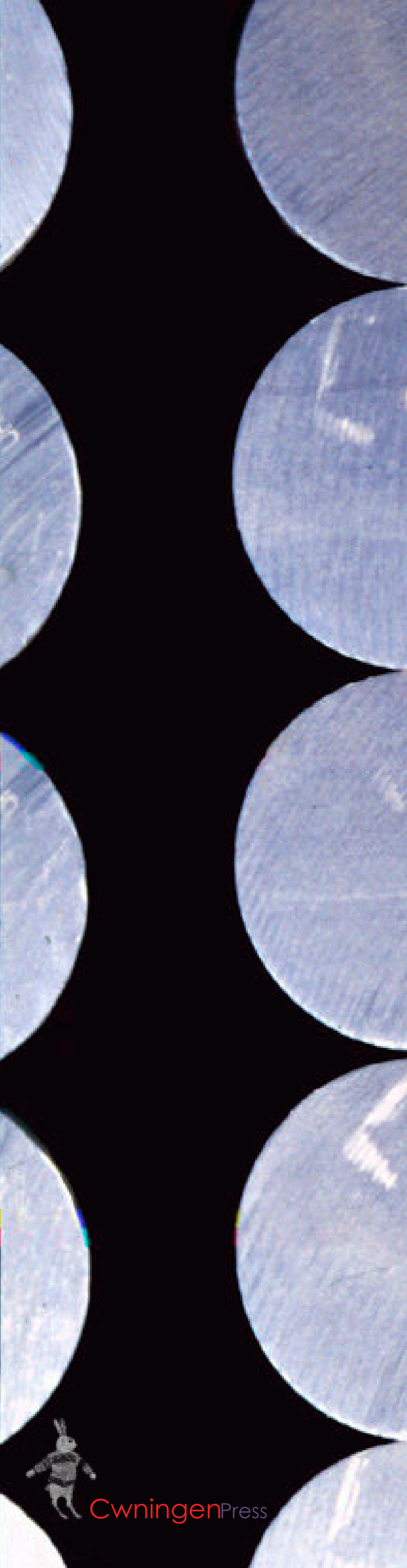
Aluminium Recyclability and Recycling

Aluminium is almost infinitely recyclable and this is well understood. This research identifies that aluminium-based projects dating back to 1950 that have been disassembled have all been recycled. 1950 is the first year of entries in IAI's global mass flow model. The research reviews the reasons why buildings are demolished and rates of material recovery at the end of use. Key examples of short life and relocatable architecture are set out, alongside the future role of Design for Disassembly [DfD]. This research also identifies that there is a much wider up take of cast aluminium components in architecture than may have been expected.

Written by Michael Stacey.

The ***Towards Sustainable Cities Research Programme*** is funded by the International Aluminium Institute [IAI] and undertaken by Michael Stacey Architects with KieranTimberlake and the Architecture and Tectonic Research Group [ATRG] of the University of Nottingham. The research is structured around the primary benefits of aluminium, as articulated by the *Future Builds with Aluminium* website (*http://greenbuilding.world-aluminium.org*), which is a sector specific component of the *Aluminium Story* (*http://thealuminiumstory.com*). *Towards Sustainable Cities* is a three-year programme quantifying the in use benefits of aluminium in architecture and the built environment.

Loblolly House, Taylors Island, Maryland, USA,
architects KieranTimberlake,
photographer Peter Aaron



Aluminium and Life Cycle Thinking
Towards Sustainable Cities

Aluminium and Life Cycle Thinking, written by Stephanie Carlisle, Efrie Friedlander, and Billie Faircloth of KieranTimberlake, with further input from Michael Stacey and the Architecture and Tectonics Research Group [ATRG] at the University of Nottingham. This forms part of the **Towards Sustainable Cities: Quantifying the In-Use Benefits of Aluminium in Architecture and the Built Environment Research Programme**, funded by the International Aluminium Institute [IAI] and undertaken by Michael Stacey Architects with KieranTimberlake and ATRG.

The **Towards Sustainable Cities Research Programme** is structured around the primary benefits of aluminium, as articulated by the The Future Builds with Aluminium website (http://greenbuilding.world-aluminium.org), which is a sector-specific component of The Aluminium Story (http://thealuminiumstory.com). Towards Sustainable Cities is a three-yearprogramme quantifying the in-use benefits of aluminium in architecture and the built environment.

A primary aim of this research is to quantify the in-use carbon benefits arising from the specification of aluminium in architecture and the built environment, to complement the relatively well-understood emission savings from the use of aluminium in transportation applications and through the recycling of aluminium scrap. A vital goal of this research is to quantify the potential contribution of aluminium towards the creation of sustainable cities – a key task now that over half of humanity lives in urban areas.

Life cycle thinking challenges architects, engineers, and contractors to be mindful of the life history of any manufactured product, and more specifically, to understand the inputs (energy and water) and outputs (emissions to the environment) that result from the transformation of matter into product and from product to disposal. This report uses Life Cycle Assessment, a modelling method, to quantify and compare the environmental impacts and benefits associated with aluminium building components to those associated with alternative materials.

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