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TOPICAL COLLECTION

Life cycle thinking: towards the sustainable management of resources in aluminium production

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Abstract

The problem of the deterioration of the human environment and natural resources and its consequences for economic and social development have received great interest over the past few decades. To facilitate sustainable development, it has become imperative to manage the use of resources in an environmentally conscious manner. To this end, life cycle management is widely considered to be the only efficient approach enabling sustainable resource management and sustainable development. This paper focuses on the life cycle inventory of aluminium production, which—due to its full recyclability—is an excellent example of "cradle-to-cradle" and life cycle thinking. Life cycle inventory is considered the key but also (in most cases) the most demanding step in the assessment of the environmental impact of a product or process. The quantified life cycle inventory for aluminium described in the present work should provide useful material for environmental managers, product designers and decision-makers in industry when they attempt to integrate environmental considerations into their respective activities.

Keywords Aluminium · Life cycle management · Life cycle inventory · Resources management · Energy resources · Waste management

Introduction

Natural resources are crucial to civilization as we know it today. However, these resources are not infinite; indeed, they are scarce in or absent from many areas around the globe. A lot of work has been performed in this field, especially since the early 1980s, when the Brundtland Commission introduced the concept of sustainability (UNEP 2004). In this context, there has been growing concern about the problem of the accelerating deterioration of the human environment and natural resources and the consequences of that deterioration for economic and social development. Environmental problems are global. Also, it is in the common interest of all nations to establish policies for sustainable development. It has become imperative to manage the use of resources in an environmentally conscious manner that promotes sustainable development. There are two main reasons for this: to keep or even improve the current relatively high standards of living in the developed world, and to provide the foundations for the developing world to attain higher standards of living. The life cycle management (LCM) of each resource is widely considered the only efficient method of achieving this goal (e.g. Shi and Li 2019; Stark 2011; Hertwich 2005).

Energy and water are two environmental considerations that must be accounted for during the whole life cycle of a product. Just as for waste, environmental concerns can be analysed particularly effectively using two interrelated techniques:

(a) *The product life cost*. In the past, this has primarily been a way of assessing "cost of ownership" (which includes capital cost, operating costs, servicing and maintenance, and final disposal) throughout the prod-

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uct's life cycle. This concept can, however, be extended to cover the product's impact on the environment and the energy needed. In the concept of life cycle thinking, it is important to account for the fact that any purchased material requires energy during the life cycle stages from the extraction of raw materials to manufacture.

(b) *The product life cycle approach*. This approach considers the interrelationships of all life cycle stages from raw material extraction to product manufacture, the product use phase, and finally its disposal (which may include product recycling to create new raw materials).

This work discusses the concept of LCM, focusing in particular on the life cycle inventory of aluminium, which is considered an excellent example of "cradle-to-cradle" and life cycle thinking due to its full recyclability. Life cycle inventory is the second step in the methodology of life cycle assessment and is often the most demanding one due to the data required. In life cycle inventory, the aim is to estimate resource consumption, the emissions and wastes generated, and the energy required throughout the life cycle of the system or product (e.g. Bianco and Blengini 2020; Mack-Vergara and John 2017; Fthenakis et al. 2009). In this paper, an analysis of all the inputs and outputs involved in the production of aluminium is provided. The life cycle inventory of aluminium provides important data for environmental managers, product designers and decision-makers in industry who need to integrate environmental considerations into their respective activities.

The concept of life-cycle management

The life cycle of a product

The product life cycle is characterised by five distinct phases, namely the extraction of raw materials, manufacturing, logistics, use and end-of-life management. For most products, the use phase is far longer than the other life cycle phases, and there may also be periods of storage and non-use between the stages. It should be highlighted that among the end-of-life management strategies that are currently available, reuse is the one with the lowest environmental impact, as it involves the fewest stages (Agrawal and Singh 2019).

Products can have totally different environmental impacts during different life cycle stages. Therefore, the whole of the life cycle of a product needs to be considered from an environmental perspective. For example, some materials may have adverse environmental consequences when extracted or processed, but may then be relatively environmentally benign during the use phase and easy to recycle. Aluminium is a good example of such a material. On the other hand, for the vast majority of industrial products (e.g. a washing machine), most of the environmental impact of the product occurs during its use phase—mainly due to water and energy consumption, which in turn generate water and air pollution, as well as solid waste (Koroneos et al. 2009). For instance, most of the solid waste generated by a washing machine comes from the packaging of the washing machine and the disposal of the machine at the end of the product's useful life. However, in practice, these two life cycle phases contribute less than 15% of the total solid waste produced by the washing machine during its life cycle. Still, it is very important to take the packaging of the washing powder and other consumables into consideration during the washing machine's life cycle. This example illustrates how careful one needs to be when considering the environmental profile of a product: every aspect of its use should be considered, while the "system boundary" should be drawn carefully and broadly enough to give a true reflection of the product's environmental burden.

Using life cycle assessment

Life cycle assessment (LCA) is a process for (a) evaluating the environmental burdens associated with a process, activity or product by identifying and quantifying the energy and materials used and the wastes released into the environment during the process, activity, or product's life, (b) assessing the impacts of the utilization of that energy and those materials and the release of that waste into the environment, and (c) identifying and evaluating opportunities to improve the environmental impact of the process, activity, or product. LCA is considered a core element of LCM and is used for a variety of industrial applications, including aluminium materials and products (e.g. Jiang and Wu 2019; Banias et al. 2016; Michailidou et al. 2016; Goedkoop et al. 2015; Guinée et al. 2011; Finnveden et al. 2009). This assessment includes the entire life cycle of the product, process or activity, encompassing the extraction and processing of raw materials; manufacture, transportation and distribution; use, reuse and maintenance; and recycling and final disposal (Costa et al. 2019). LCA is holistic and seeks to quantify environmental impacts. It investigates all inputs to and outputs from the system at all stages during the entire life cycle of a product or service. It also categorises environmental impacts in terms of the use of resources, the impact on human health, and the consequences for the wider world (the so-called ecological consequences).

The framework within which life cycle assessment is carried out is shown in Fig. 1 (International Standards Organization 2006). Two main activities are preceded by a vitally important planning phase and followed by extended interpretation, which normally involves checking the results against the initial goals and for self-consistency. There are two main activities in an LCA: (a) the inventory analysis

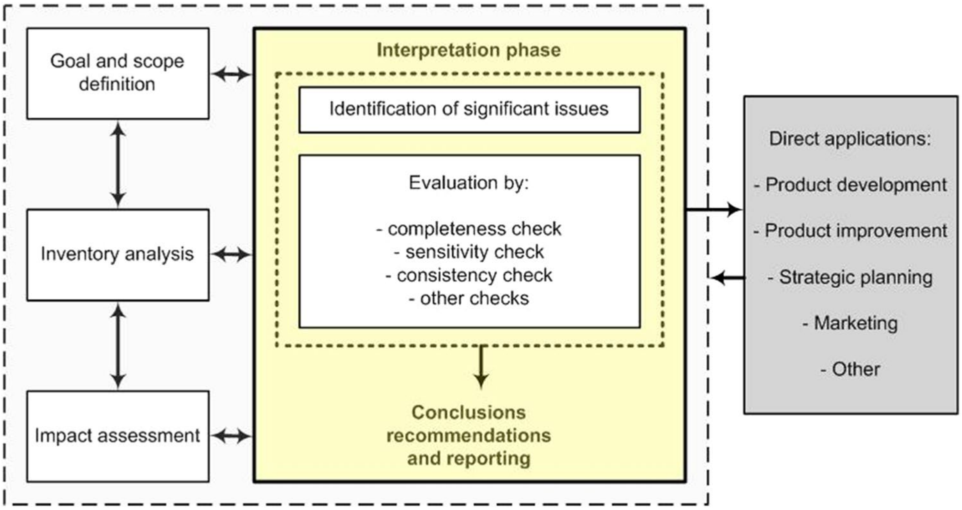


Fig. 1 The concept of life cycle assessment

step, which describes the emissions that occur and the materials and resources used during the life of a product, and (b) the impact assessment step, which looks at the impacts of emissions and the use of resources and raw materials on the environment. Figure 2 provides a general overview of the structure of an impact assessment method. The life cycle inventory results are related to "endpoints", which are issues of environmental concern, and "midpoints", which reflect the mechanisms that lead to environmental effects. The LCA methodology has three standard endpoints: the damage to (a) human health, (b) ecosystems and (c) natural resources.

Key principles of life cycle management

LCM is essential for sustainable consumption and production. It goes beyond the traditional focus on production sites and manufacturing processes. Within the concept of LCM, the environmental, social and economic impacts of a product over its entire life cycle, including the consumption and end-of-use phases, are taken into account. The key principles of extended producer responsibility (EPR) (Shan and Yang 2020; Pazoki and Zaccour 2019; Tsarouhas et al. 2015; European Commission 2014, 2011; Achillas et al. 2011) and integrated product policy (IPP) (Rubik and Scholl 2002; European Commission 2000) are strongly promoted. According to EPR, producers should take responsibility for their products from cradle to grave and should therefore develop products that present improved performance throughout all stages of the product life cycle. There are opportunities for improved performance at each stage of the life cycle. Similarly, the goal of IPP is to reduce a product's resource use and emissions to the environment, as well as to improve its socioeconomic performance throughout the life cycle. This may facilitate links between the economic, social and environmental dimensions of an organisation and throughout its entire value chain. In brief, LCM promotes:

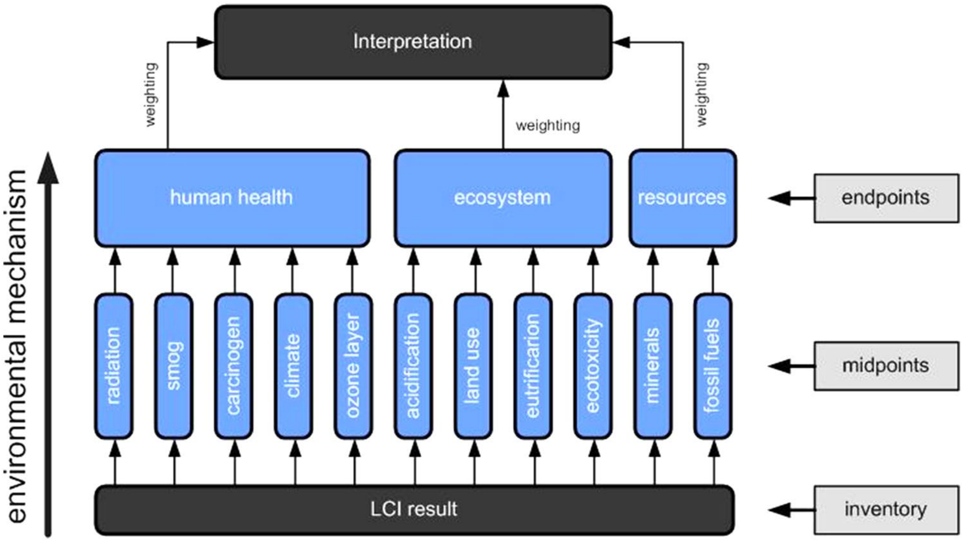


Fig. 2 Structure of the impact assessment methodology

(a) Awareness that strategic selections are not isolated; they influence the overall system
(b) Long-term thinking and consideration of all environmental and social issues
(c) System thinking in terms of life cycle phase (production, use, waste management, etc.), geographic region and environmental medium (air, water or soil)
(d) Better-informed decisions based on data sourced from all the different parts of a system or life cycle.

Turning life cycle management into practice

Decisions are increasingly being based on life cycle information. The concept of life cycle management (LCM) needs to be incorporated into everyday life. For instance, how industries and homes currently use water and what those industries and homes release into water systems are key life cycle considerations. Using life cycle information, industrial processes can be redesigned in a way that preserves water quality and improves access to clean water for local people. Along the same lines, a life cycle approach to community planning and development can lead to fewer environmental impacts from materials used, construction practices, and waste management, as well as from the energy and water used by people living and working in the community.

In the business world, a product designed with improved environmental, social and economic life cycle performance can provide benefits to the company, which can then be further communicated to its customers. A large portion of businesses prefer to use product declarations or other labels to market environmental and social attributes to their customers. Moreover, a number of international standards have been developed to allow business-to-business communications and environmental product declarations. Such declarations need to be based on a life cycle study and to inform the public about the environmental impacts of the component or product being purchased over its life cycle. Among others, declarations exist for building and construction products, refrigerators and other electronic appliances, chemicals, cars and dairy products.

Life cycle thinking that influences product design, strategic planning, procurement and sales assists businesses in (a) enhancing their image and the value of their brands, (b) finding new ways for marketing and sales departments to communicate and interact with customers, and (c) sharing life cycle information with suppliers, customers and other links of the supply chain. As regards the latter, risks might relate to the environment, human health, safety and finance, while opportunities could include those to grow market share, enhance the brand's image, effectively use materials and innovate. Through collaboration, businesses can find new ways to improve output while optimising their use of time, money, labour, and material input.

All of the aforementioned initiatives need to be considered within the concept of LCM. The latter can be put into practice in numerous ways through the use of available tools. The public helps to bring life cycle thinking into purchasing decisions by referring to ecolabels, sustainability indices, and company reports on environmental and social issues. Authorities take a life cycle approach to policy making by involving a wide range of stakeholders, performing life cycle modelling, or instigating new policy approaches (such as integrated product policy). In the private sector, companies, engineers and designers apply life cycle thinking when designing products and services by performing studies based on life cycle assessment, implementing design-for-environment programs, and using management systems oriented toward products or facilities. Quantitative and qualitative tools for mapping life cycles and measuring impacts continue to evolve as more and more professionals apply life cycle thinking and ask for life cycle information.

Life cycle thinking in the case of aluminium

The basic characteristics of aluminium

As already discussed, it is vitally important to consider the life cycle of every material used in the life cycle of a product so that appropriate processes can be designed to reduce the product's environmental impact and simultaneously achieve a high level of recycling. Aluminium is a perfect example of this. There have been a number of attempts to analyse the impacts of the production of aluminium (Albuquerque et al. 2019; Farjana et al. 2019; Guo et al. 2019; Peng et al. 2019; Yang et al. 2019; Grimaud et al. 2016; Niero and Olsen 2016; Paraskevas et al. 2015; Hong et al. 2012; Liu and Müller 2012; Hiraki and Akiyama 2009), which underlines the importance to scientists and industry of quantifying the life cycle impacts of this metal and the need for a thorough life cycle inventory of aluminium, as presented below.

Even though aluminium was first produced just over a century ago, this relatively "young" metal is the world's second most commonly used metal. It is so ubiquitous in modern life that it is difficult to imagine a world without it. Even though the production of aluminium is one of the most polluting of all material production processes due to the large amount of natural resources and electricity required, the high recyclability of aluminium could reduce the need to produce more of it, thus helping to lower the environmental burden of aluminium production, including the use of natural resources. In this context, a "cradle to cradle" life cycle for an aluminium product system can be modelled based on various process steps such as those displayed in Fig. 3.

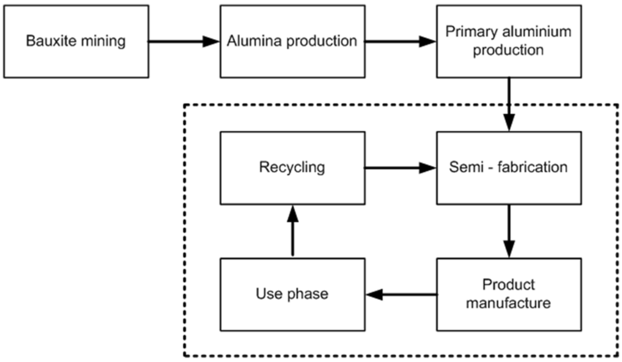


Fig. 3 “Cradle to cradle” life cycle of aluminium products

Aluminium output has increased by a factor of 13 since 1950, making it the most widely used nonferrous metal. Globally, production plants are mainly located where suitable electrical energy resources are available (Koroneos et al. 2009). Figure 4 illustrates the main areas in which aluminium is produced (European Aluminium Association 2019).

Aluminium has a unique combination of properties, making it a versatile, highly usable and attractive construction material. It is a strong, lightweight metal and a good conductor of heat and electricity. Its name originates from the Latin word *alumen*. Aluminium was probably first isolated by Oersted in 1825, who obtained it by heating potassium amalgam with anhydrous aluminium chloride. Aluminium is soft and has very good elasticity, similar to that of gold, but it does not have the same ductility as gold. It shows good formability; it can be extruded, cast, drawn or milled. Among its strongest qualities are the ease with which it can be machined and its suitability for forming under both hot and cold conditions. Also, aluminium is relatively easily joined through welding, soldering, bonding or riveting. It is a nonmagnetic, nontoxic material, as it does not burn or produce toxic fumes. Aluminium is chemically active, reacting strongly with oxygen and other elements. It can be anodised, painted or coated, and it is highly resistant to corrosion, as a transparent protective oxide film forms on its surface under atmospheric conditions. Aluminium is weakly affected by a large number of acids but vulnerable to strong alkalis. Although it is the third most abundant material globally, it is not found in the elemental state in nature; aluminium is generally extracted from the ore bauxite. Finally, one of its most important advantages is the fact that it is 100% recyclable.

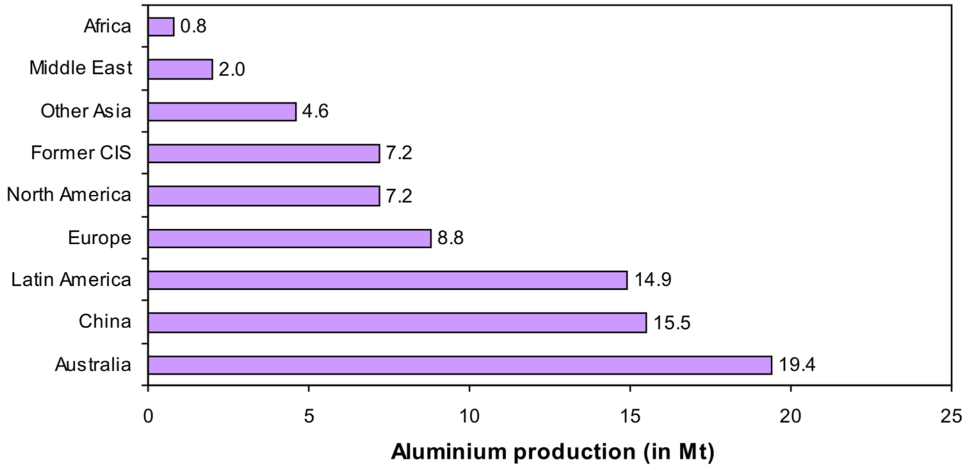
Aluminium is produced through the Bayer and Hall–Héroult processes (International Aluminium Institute 2019; Habashi 1998):

(a) The first stage in the production of aluminium using the Bayer process is the generation of aluminium oxide (alumina) from bauxite. The bauxite is ground into very small pieces and converted into a pulp with sodium hydroxide (NaOH). The resulting solute must be purified by settling and filtering to form the “main” liquid and red clay. This liquid is then cooled. Next, aluminium hydroxide trihydrate is prepared by adding a delicate crystalline hydrated aluminium oxide in the form of crystalline particles. Aluminium oxide is then produced through calcification.

(b) The Hall–Héroult process is named after the two researchers who developed the process independently of each other in 1886. This process involves the electrolytic reduction of aluminium oxide. The Hall–Héroult process is the basis for the large-scale production of aluminium via molten salt electrolysis. In practice, aluminium is currently produced exclusively by this process (Norgate et al. 2007).

The data used in the present work are based on studies performed by the European Aluminium Association

Fig. 4 Worldwide production of aluminium

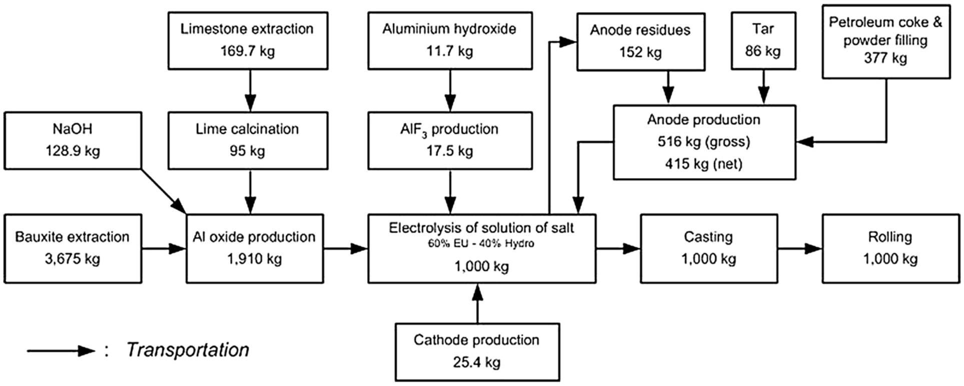


(1995). These data reflect the status of the aluminium industry, including aluminium ore extraction activity, in Europe. The values assumed for the production of primary aluminium and for the rolling and recycling of the metal reflect European averages. Specific industries have provided values for other stages of the life cycle, which were used as guidelines. Moreover, it was assumed that 60% of the energy used in the production of aluminium is produced within Europe, with the remaining 40% produced in metal-producing countries such as Canada and Iceland. Thus, corresponding averages are taken into consideration in the calculations. The EAA's data on the production of primary aluminium and for the rolling and recycling of the metal are very detailed. In the analysis that follows, primary aluminium production is compressed into two stages: the production of aluminium oxide and the production of unwrought aluminium. This study includes various processes associated with the transportion required to produce primary aluminium in bar form.

System definition

The various processes involved in the production of primary aluminium in bar form are shown in Fig. 5. All of the steps and processes needed to produce the end product are taken from the EAA's studies and were included in the calculation of the total inventory. The only exception is caustic soda; data for this particular inventory originate from a study conducted by the Association of Plastic Manufacturers in Europe (1994). Figure 5 also shows the transportation aspects considered in the study. The origins of the data used in this work are presented in Table 1.

Fig. 5 Flow diagram for the production of primary aluminium



Extraction of raw materials

The mining of bauxite is the first step in aluminium production (e.g. Durucan et al. 2006). More than 130 million tons of bauxite are mined every year globally. Bauxite is extracted in Australia, Central and South America (Jamaica, Brazil, Suriname, Venezuela and Guyana), Africa (Guinea), Asia (India, China) and parts of Europe (Greece and Hungary). In many of these regions, bauxite is the only valuable natural resource. Data on bauxite extraction were obtained from SAEFL (1992), as updated by the European Aluminium Association with the assistance of the International Primary Aluminium Institute, using additional data from selected bauxite mines. The following geographical regions were considered in the present study; Guinea, Australia and Europe. Bauxite was assumed to be transported to Switzerland for further processing. Data on transportation were calculated according to the weight transported and the distance from the bauxite source.

Sodium chloride is either extracted as a mine salt that is subjected to further processing, or it is directly extracted from soil layers rich in salt as a solute. The latter is used for the concurrent production of sodium hydroxide (caustic soda) and chlorine gas (chlor-alkali electrolysis), as illustrated in Fig. 6. The data for the whole life cycle were obtained from the Association of Plastics Manufacturers in Europe (1994).

Data on the extraction of limestone were sourced from the European Aluminium Association, who obtain the data directly from SAEFL (1992) and EMPA (Swiss Federal Laboratories for Materials Testing and Research 1989). Transportation from the extraction site to the facility where the limestone is calcinated was also accounted for; an average transportation distance of 500 km was assumed.

Production of aluminium

Lime is produced by calcinating limestone. The data for this process were taken from EMPA (1989), SAEFL (1992) and two European companies. The process is typically performed in alumina plants.

Table 1 Data sources for the various processes

Process	Data source
Bauxite mining	SAEFL (1992)
NaOH production	Association of Plastics Manufacturers in Europe (1994)
Limestone mining	SAEFL (1992); EMPA (1989)
Limestone calcination	SAEFL (1992); EMPA (1989); 2 European plants
Alumina production (Al_2O_3)	European Aluminium Association (1995)
Anode production	5 European plants
Tar production	1 European plant
Petroleum coke production	2 European plants
Powder filling production	1 European plant
Cathode production	6 European plants
Aluminium fluoride production	2 European plants
Molten salt electrolysis	All European foundries
Foundries	European Aluminium Association (1995)
Transportation	European Aluminium Association (1995)

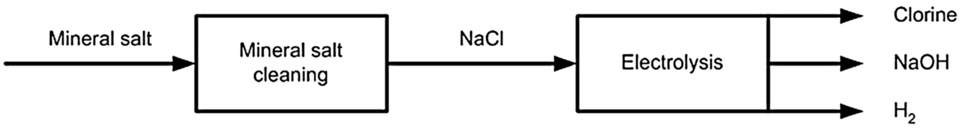


Fig. 6 Production of chlorine and caustic soda

Alumina, the raw material for primary aluminium production, is extracted from bauxite. The conversion of bauxite to alumina and the processing of alumina into aluminium are both energy-intensive processes (Tan and Khoo 2005). In the Bayer process, the production of alumina requires bauxite, sodium hydroxide and lime. Bauxite must be processed into pure aluminium oxide (alumina) before it can be converted to aluminium by electrolysis. In total, 4 tons of bauxite are required to produce 2 tons of alumina, which in turn produces 1 ton of aluminium. The data on alumina production came from companies located in various areas. Just as for the transportation of bauxite, distances and transported quantities were considered for different modes of alumina transportation. 63% of alumina originates in Europe; other major alumina producers are Jamaica (15.3%), Suriname (15.3%), Australia (8.5%) and Guinea (2.0%).

Anodes are manufactured from petroleum coke, tar and anode residues. The transportation of petroleum coke and tar is also accounted for in the inventory. Only emissions due to the transportation, not the combustion, of crude oil were included in the inventory. A similar procedure was followed for the production of tar to that used for coal. Following electrolysis, anodes that are not consumed reenter the anode production process. Approximately 0.6 g of anode material are consumed to produce 1 kg of aluminium. Considering the reuse of anode residue, this figure drops to 0.42 g of anode material consumed per 1 kg of aluminium.

Similar to the anode, the cathode consists mainly of coal. However, very little of the cathode is consumed during the electrolysis process: on the order of 0.02–0.04 kg of cathode material per kg of aluminium. This consumption is due to the decomposition of the cathode at the end of the furnace's useful life.

During the production of aluminium, aluminium fluoride is used as an additive in the electrolysis of the salt solution. Aluminium fluoride is produced from aluminium hydroxide and calcium fluoride using sulfuric acid. Data from the European Aluminium Association on the production of aluminium oxide were modified appropriately and used to reflect the production of aluminium hydroxide. Data on the production of aluminium fluoride were sourced from two European plants. The transportation of aluminium fluoride until it was used in electrolysis was also taken into account.

The electrolysis of a salt solution is the industrial process most commonly used to produce primary aluminium. In this process, Na_3AlF_6 is mixed with various additives and molten metal. Aluminium oxide is then added. Approximately, 2–6% of the aluminium oxide decomposes in the Na_3AlF_6 bath (which is maintained at 950 °C) into aluminium ions (Al^{3+}) and oxygen (O^{2-}). Thus, the Na_3AlF_6 plays the role of the electrolyte. A voltage (approximately 4–5 V) is applied between the anode and cathode in order to dissociate aluminium oxide into aluminium ions and oxygen ions. The oxygen ions are attracted to the anode, where they lose their electrons and are therefore converted into oxygen atoms. The oxygen atoms pair up and create oxygen bubbles:

$$O^{2-} - 2e^{-} \rightarrow O \text{ and } 2O \rightarrow O_2 \uparrow .$$

At the cathode, the aluminium ions gain electrons and form a metal alloy:

$$Al^{3+} + 3e^{-} \rightarrow Al.$$

The molten Al is heavier than Na_3AlF_6 and therefore collects at the bottom of the container. This process only requires electricity as its energy source. The container's electrical resistance generates the heat needed to melt the electrolyte. The consumption of anode material during the electrolysis produces about 25% of the total energy required. The energy supply model for electrolysis mentioned above (60% of the energy is produced within Europe, 40% is produced in metal-producing countries) was also assumed in the present work. The assumed proportion of the energy produced in Europe by each type of power source (based on the assumptions of the European Aluminium Association) is summarized in Table 2. This table also lists the weighted global average contributions of the various types of energy sources; these values were also used in the study.

The product of the electrolysis of the salt solution reacts initially with metal alloys (aluminium–magnesium alloy), which is cleaned and then cast into the desired form (usually aluminium bars). Aluminium casting methods are very powerful and versatile techniques for manufacturing semi-finished or finished products with intricate shapes. Those techniques are continuously improved and developed to satisfy the needs of users and to allow aluminium products to penetrate new markets. Cleaning is performed using either a gas (most frequently nitrogen containing 2% chlorine) or a fluid (usually salt or sodium fluoride). Both the types and the quantities of the alloys and materials involved depend on the desired end product. The production of a 1000-kg aluminium bar requires 1010 kg of melted aluminium. The excess 10 kg is recycled. Since the recycling of 10 kg of aluminium has a negligible influence on the final result, it was not considered in the present study.

Raw aluminium bars are initially processed into 0.7 mm thick aluminium foils, which are then used to produce other products. During this process, the bars are cut before being heated in an oven. The hot cylindrical billet of aluminium is then pushed through a shaped die and it undergoes a cold extrusion process. The resulting aluminium sheet is cut into pieces before it is delivered. Residues of aluminium that result from the production process are recycled using various types of furnaces. 0.7 mm thick aluminium foils are extracted into 7–12 µm sheets. Data for this process are available from the European Aluminium Association, which sources data from the largest foundries in Europe.

Transportation of aluminium

In the inventory considered here, various types of transportation were assumed for the most important raw materials in the production of aluminium. These types of transportation are shown in Table 3, as are the estimated average distances, which were calculated by the European Aluminium Association based on data obtained from the ESU-ETHZ (1996), with the exception of the internal transportation of aluminium within foundries, for which the energy data were taken directly from the European Aluminium Association.

Recycling of aluminium

The known reserves of high-quality bauxite are sufficient to supply our aluminium needs for over 300 years. A great advantage of aluminium is that it can be fully recycled without any loss of quality or degradation of its properties. In that sense, recycling is a major consideration for the continuous use of aluminium following the production and use phases in the aluminium life cycle; indeed, it is one of its key attributes, with far-reaching economic, ecological and social implications. The recyclability of aluminium-based products depends heavily on the collection method used, the type of material and the country in which it is performed. More than half of all the aluminium currently produced in the European Union comes from recycled raw material, and this proportion is constantly increasing. In total, recycling

Table 2 Energy supply model for electrolysis during aluminium production

Energy source	Contribution to energy produced in Europe for aluminium production (%)	Contribution to imported energy (i.e. not generated in Europe) for aluminium production	Weighted average global contribution to energy used for aluminium production (%)
Hydroelectric power	43.8	100%	66.3
Nuclear energy	24.7	–	14.8
Coal	22.6	–	13.6
Natural gas	5.4	–	3.2
Oil	3.5	–	2.1

Table 3 Types of transportation used in the production of aluminium (40% of which is imported)

Material	Distance (km)	Type of transportation
Bauxite	7917	Trans-oceanic freighter
Limestone and lime	500	Domestic cargo ship
NaOH	500	Domestic cargo ship and truck
Alumina	4587 + 68	Trans-oceanic freighter + railway
Petroleum coke	1.000	Trans-oceanic freighter
Tar	250	Domestic cargo ship and truck
Aluminium fluoride	300	Railway and truck
Aluminium (produced)	Energy data	Tractor and truck
Raw aluminium	300 + 100	Domestic cargo ship + railway
Imported aluminium (50% from Canada, 50% from Iceland)	4650	Trans-oceanic freighter

Table 4 Potential recycling rates for aluminium in Europe, including Switzerland (data acquired from the European Aluminium Association and Alcan)

Aluminium products	Recycling rate in Europe, including Switzerland (%)
All products	60
Beverage cans	85
Canned food (e.g. food dishes, fish cans, pet food)	48
Packaging (excluding metal containers)	25
Cars	95
Construction	85

saves up to 95% of the energy that would have been used for primary aluminium production while also avoiding the corresponding emissions, including greenhouse gases.

In Table 4, the recycling rates of various aluminium products after consumption in Switzerland are presented. The recycling of aluminium during the production of this metal is widely known as internal recycling and was considered in the life cycle inventory. Rates of internal recycling can be as high as 100%. Here, we only consider the recycling of aluminium after its use phase. Data on the recycling of aluminium were sourced from the European Aluminium Association.

In view of domestic energy constraints, the growing demand for aluminium and the small number of bauxite mines, there is a strong drive to maximise the collection of all available aluminium and to develop the most resource-efficient scrap treatments and melting processes. The high value of aluminium scrap is a key incentive and a major economic impetus for recycling.

Life cycle inventory

Table 5 presents the life cycle inventory for the production of aluminium sheets. The data sources for the various processes are presented in Table 1.

Conclusions

LCM can promote more sustainable rates of production and consumption while supporting the effective use of limited financial and natural resources. The value of invested capital can be increased by optimising output and deriving more benefit from the time, money and materials used. Experts from industry and public authorities agree that making the life cycle approach the key concept in product and service design should stop and possibly reverse some of the recent negative trends in environmental management.

In the case of aluminium, which was considered in depth in the present work, the full recyclability of this material means that, in practice, it is not consumed but rather used. Therefore, the life cycle of an aluminium product is usually not “cradle-to-grave” but rather “cradle-to-cradle”. Summarising, aluminium has unique recycling properties, as its quality is not impaired by recycling, meaning that it can be repeatedly recycled, saving significant quantities of energy. Also, the recycling of aluminium is economically viable, as it consumes significantly less energy than required to produce the equivalent amount of primary aluminium. Therefore, the recycling of aluminium is self-supporting, especially due to the high value of used aluminium.

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Table 5 Life cycle inventory for the production of aluminium sheets (0% recycling rate)

Product	Unit	Quantity
Aluminium sheet (functional unit)	kg	1000
Waste quantities produced during the production of aluminium		
Dissolution of cathode	kg	16.6
Iron cathode rods	kg	6.1
Metal waste for recycling	kg	12
Waste treatment required during the production of aluminium		
Waste directed to a chamber of inactive material	kg	176
Waste directed to an incineration chamber	kg	34.8
Waste directed to a reactive chamber	kg	1.08
Waste discarded for decomposition	kg	995
Energy resources, commercial fuels (primary energy sources required)		
Lignite	kg	217
Natural gas	Nm^3	451
Coal	kg	1610
Crude oil	kg	1300
Uranium	gr	78
Wood	kg	15.8
Potential energy of water	MJ	48,000
Sources of raw materials required during the production of aluminium		
Bauxite	m^3	8.44
Iron ore	kg	3710
Limestone	kg	0.0425
Coal	kg	174
Secondary SO_2	kg	10.7
Sand	kg	19.6
Mineral salt	kg	0.0185
CaF_2	kg	54.5
Insulation boards	kg	25.4
Isolating blocks	kg	3.4
Other (liquid and gas)	kg	5.2
End products produced		
Aluminium bars	kg	1000
Iron	kg	13

Air pollutants during the production of aluminium	Unit	Process	Heat	Electricity	Transport	Without cleaning	Total
Dust/particles	g	1700	400	4400	200	14,900	21,600
Benzene (C_6H_6)	g		11.1	4	1.2		16.3
Polycyclic aromatic hydrocarbons	g			0.1		39.8	40
Aromatic hydrocarbons	g		20.3	35.1	2.9		58.3
Halon 1301	g		0.247	0.036	0.026		0.309
Halogen hydrocarbons	g		0.00004	0.00196	0.00001		0.00201
Methane (CH_4)	g		6200	11,300	500		18,000
NMVOCs	g		8200	1400	1000	600	11,100
Carbon dioxide (CO_2)	g	1,540,000	660,000	3,250,000	370,000	2,400,000	8,220,000
Carbon monoxide (CO)	g	60,000	700	600	300	100	61,600
Ammonia (NH_3)	g		0.2	14.1	0.1	0.1	14.5
Hydrofluoric acid (HF)	g		1.6	75.4	0.9		77.9
Nitrous acid (N_2O)	g		10.6	27.5	7.5	0.1	45.7
Hydrochloric acid (HCl)	g		17	709	9	14	748

Table 5 (continued)

Air pollutants during the production of aluminium	Unit	Process	Heat	Electricity	Transport	Without cleaning	Total
Sulfur oxides (SO_x)	g	14,100	5400	14,500	4700	17,900	56,500
Nitrogen oxides (NO_x)	g	200	3100	7800	1300	4600	17,000
Lead (Pb)	g		0.21	0.67	0.22		1.1
Cadmium (Cd)	g		0.106	0.042	0.123		0.271
Manganese (Mn)	g		0.008	0.332	0.002		0.342
Nickel (Ni)	g		3.1	3.23	2.54		8.88
Mercury (Hg)	g		0.016	0.103	0.002		0.121
Zinc (Zn)	g		1.01	1.04	0.25		2.29
Metals	g		21	199	15		236
Radioactive substances	kBq		120,000	6,520,000	40,000		6,680,000
Aldehydes	g					0.1	0.1
CF_4	g	400					400
Fluoride ions	g	750				74	824
Hydrocarbons	g					71.9	71.9

Water pollutants during the production of aluminium	Unit	Process	Heat	Electricity	Transport	Without cleaning	Total
Waste water	m^3	0.03				1.75	1.78
Biological oxygen (BOD)	g		2.29	0.68	0.26	0.29	3.51
Chemical oxygen (COD)	g	0.1	44.4	15.5	5.5	20.3	85.9
Adsorption of organic halogens (e.g. Cl^-)	g		0.179	0.027	0.019		0.225
Suspended solids	g	40	3160	790	310	700	5010
Phenol	g		7.46	1.13	0.78		9.37
Toluene (C_7H_8)	g		6.16	0.92	0.65		7.73
Polycyclic aromatic hydrocarbons (PAH)	g		0.7	0.1	0.1	17.1	17.9
Aromatic hydrocarbons	g		44.4	6.7	4.7		55.8
Chlorinated hydrocarbons	g		0.0485	0.009	0.0048		0.0623
Fats/oils	g		1370	210	140		1730
Soluble organic carbon (DOC)	g		3.1	2.23	0.01		5.35
Total organic carbon (TOC)	g		611	214	44		869
Ammonium (NH_4^+)	g		52.7	21	6.1		79.8
Nitrate radicals (NO_3^-)	g		33.3	59.1	3.7		96
Nitrogenous organic radicals	g		5.13	0.82	0.65		6.6
Arsenic (As)	g		51.2	7.8	5.9		64.9
Chloride (Cl^-)	g		0.56	4.6	0.02		5.18
Cyanite (CN^-)	g		29,000	18,500	3000	2700	53,200
Phosphate, phosphate radicals (PO_4^{3-})	g		0.2	0.081	0.021		0.302
Sulfate radicals (SO_4^{2-})	g		16	136	1		153
Sulfide, sulfur ions (S_2^-)	g		2000	16,000	200	400	18,500
Inorganic salts and acids	g		1.58	0.28	0.17		2.03
Aluminium (Al)	g		20,800	11,300	2100	400	34,600
Barium (Ba)	g		260	2290	10		2560
Lead (Pb)	g		150	200	14		365
Cadmium (Cd)	g		1.4	12.7	0.1		14.1
Chromium (Cr)	g		0.069	0.131	0.006		0.206
Iron (Fe)	g		3	22.8	0.1		26
Copper (Cu)	g		120	970	10		1110
Nickel (Ni)	g		1.4	11.4	0.1		12.8
Mercury (Hg)	g		1.4	11.5	0.1		13
Zinc (Zn)	g		0.00119	0.00372	0.00007		0.00498

Table 5 (continued)

Water pollutants during the production of aluminium	Unit	Process	Heat	Electricity	Transport	Without cleaning	Total
Metals	g		3	23	0.1		26.2
Radioactive substances	kBq		1100	60,000	400		61,500
Fluoride ions (F^-)	g		343	284	34	6	668
Sulfuric acid (H_2SO_4)	g					2.71	2.71
Organic hydrocarbons	g					823	823

Compliance with ethical standards

Conflict of interest On behalf of all the authors, the corresponding author states that there is no conflict of interest.

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