GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

TRABAJO FIN DE GRADO

MODELLING THE ALUMINUM MARKET

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Madrid

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

Modelling the aluminum market

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Chapter 1. INTRODUCTION

Aluminum is one of the most widely used metals today due to its properties, such as thermal and electrical conductivity, its versatility and, above all, its strength-to-weight ratio. Among the sectors in which it is used, two sectors that are closely related to each other stand out: the automotive sector and the aeronautical sector. The reason why aluminum stands out so much from other metals is because the aim is to create safe, yet lightweight means of transport for better performance. In addition, reducing weight not only has an impact on vehicle speed and acceleration, but also on fuel consumption. And nowadays, reducing fossil fuel consumption is one of the most discussed and most important issues in the short term.

Although it is true that aluminum is a metal widely used in many sectors, not all of them use the same aluminum alloys. There are currently 8 series of aluminum, and the first series (1xxx) represents pure aluminum, with at least 99% aluminum in its composition, which is obtained after extracting aluminum from a mineral, bauxite, and treating it. Pure aluminum has hardly any use, and what is done is to mix and alloy it with other elements to change the characteristics of the final product. The most commonly used alloys are the 6xxx series, with magnesium and silicon, which gives the metal high tensile strength and is used mainly in aircraft production.

Due to the importance of the metal for the mentioned reasons, this project aims to present the performance of the market for aluminum. In Chapter 2, the temporal evolution of the price and which indicators are related to its variations will be considered. The environmental implications and what is being done to make its production more sustainable will also be reviewed. Chapter 3, presents the whole process of production, transportation and the uses it has once the material is refined and ready to be used in the different elements and products that require its use. In order to know how these indicators affect the price, a statistical model will be developed in Chapter 5. The model will be considered data representative of the last decades in order to return the repercussion that each one of these indicators has and their relevance as determinants in the supply and demand of aluminum. Finally, Chapter 6 will present the main conclusions of the project.

Chapter 2. ALUMINUM

2.1 DEFINITION

Aluminum is one of the most widely used metals all around the world, only surpassed by steel. But this has not always been so; only 150 years ago aluminum was an extremely expensive metal, similar in value to gold. The main reason associated with its high cost, was the complexity of extracting the aluminum from its ore at that time. However, nowadays it is much simple to extract it due to the advancements of technology, leading to a significant decrease in the cost of aluminum production.

Aluminum has several properties that make it an extremely valuable metal. First, its thermal and electrical conductivities make it useful in manufacturing electrical wires, in addition to copper. Secondly, and one of the main reasons why it is used, is its strength/weight ratio, being relatively strong and having a low density. In addition, it stands out for its ability to withstand corrosion, as a result of the oxide film formed over the surface. Other relevant reasons for choosing aluminum are its workability, recyclability, and cryogenic toughness.

This metal is derived from bauxite, which is a sedimentary rock that contains aluminum. After a series of diverse processes, aluminum is extracted and used. But pure aluminum, which is aluminum that contains at least 99% of pure metal, is normally mixed with other metals for its final uses. Once mixed, it receives the name of aluminum alloy, a substance of at least two elements, where one must be a metal. A large number of aluminum alloys contain between 90 and 96 percent of aluminum (Davis 1993).

There is a huge variety of aluminum alloys, mainly because a slight variation in the percentage of the elements in the mixture results in a different alloy. Alloys are classified by a four-digit system and are defined by the mass portion of each material. The first digit is the most important one, as it defines the main element, other than the aluminum, present in the mixture. The first number, therefore, gives name to the family of alloys, which are referred to as series. The second digit refers to the impurity limits, and the third and four digits to the minimum percentage of aluminum and of the different aluminum alloys.

Alloys can be classified into two different groups, wrought alloys, and cast alloys. The difference between them is that wrought alloys are created in ingot form and subsequently, worked into a solid form, through the necessary metallurgical processes. On the other hand, cast alloys are melted and molded in this form, not being meant to be worked by rolling or extrusion methods. Both groups are very similar, both in the name of the series and in the characteristics that define them. Wrought alloys range from 1xxx, to 9xxx, although 9xx is the last series and is not yet defined, as it is reserved for future uses. Casts alloys range from 1xx.x to 9xx.x. (Table 1). Each series has different combinations of elements and is used for particular purposes.

Table 1. Alloys series and designations.

Alloy	Main element	Explanation
Serie 1xxx	No major alloys	Pure aluminum, may contain a maximum of 0.1% of copper, being at least 99% aluminum
Serie 2xxx	Copper	One of the most common series, widely used in aircrafts and electrical appliances
Serie 3xxx	Manganese	Most used series, excellent resistance and workability and used for various products
Serie 4xxx	Silicon	Low melting point and used in welding rods
Serie 5xxx	Magnesium	Good saltwater corrosion resistance used in marine environments
Serie 6xxx	Magnesium and silicon	High tensile strength and used for architectural purposes
Serie 7xxx	Zinc	Extremely good weight/strength ratio and used for aeronautical pieces
Serie 8xxx	Other elements	Different properties depending on the elements mixed on each alloy of this series

Source: Own elaboration based on Davis (1993)

Besides the series of alloys, once the type of aluminum is chosen, it can be tempered to improve some properties that the material has. There are different methods for tempering and each one affects the characteristics of the metal in a different way. There are five basic types of temper designation, and each has a letter that is written as a last name after the name of the metal. These five temper types are: fabricated (F), annealed (O), strain hardened (H), solution heat treated (W), and thermally treated to create different tempers (T). Fabricated alloys are those that do not receive any special treatment, neither thermal nor strain hardening (Gilbert Kaufman, 2000).

Alloys can also have a letter after the temper type to specify a sequence of treatments on the metal, these designations are called subdivisions. The most common types of subdivisions are listed below. Tempers designations and subdivisions can be found in Table 2.

Table 2. Tempers designations and subdivisions.

Temper	Explanation	Temper	Explanation
T1	Cooled from an elevated temperature shaping process and naturally aged to a substantially stable condition	T8	Solution heat treated
T2	Cooled from an elevated temperature shaping process, cold worked, and naturally aged to a substantially stable condition	T9	Solution heat treated, artificially aged, then cold worked
T3	Solution heat treated, cold worked, and naturally aged to a substantially stable condition	T10	Cooled from an elevated temperature shaping process, cold worked, then artificially aged
T4	Solution heat treated and naturally aged to a substantially stable condition	H1	Only strain hardened
T5	Cooled from an elevated temperature shaping process, then artificially aged	H2	Strain hardened and annealed
T6	Solution treated, then artificially aged	H3	Strain hardened and stabilized
T7	Solution heat treated and overaged/stabilized	H4	Strain hardened and painted

Source: Own elaboration based on Gilbert Kaufman, (2000)

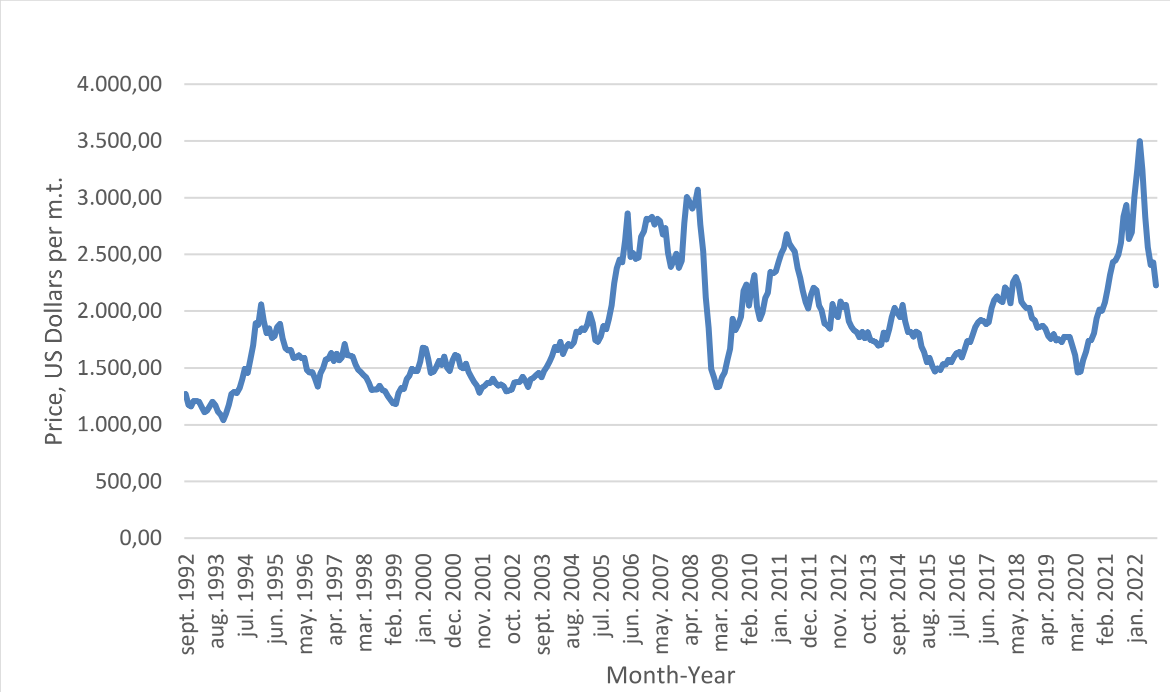
2.2 HISTORICAL PRICE FLUCTUATIONS

Mineral commodities show a great variability in prices over time. Fluctuations in metal prices have been an issue of great interest not only because of their relevance to the metallurgical industries, but also because they reflect to a large extent the variations of economic cycles. Aluminum has suffered several price peaks, fluctuating between different values, showing a lateral trend over time. Some studies analyze price fluctuations to check if they are just random or if they present certain degree of cyclicality (Roberts, 2009; Labys et al, 1998; Cashin et al 2002 and Deaton and Laroque, 1992).

Not only investors are affected by these aluminum price fluctuations over time, but also consumers and producers. Therefore, it is useful to have as much knowledge as possible about the evolution of their price and to know whether they show cyclical trends. The National Bureau of Economic Research (NBER) defines a cycle as price fluctuations which are recurrent but not periodic, consisting of an expansion and a recessionary phase.

Figure 1 shows the monthly historical evolution of aluminum price from 1992 to 2022 according to the World Bank. Two different regions are differentiated according to the distribution of the data. The first one, from September 1992 to June 2005, where, with the exception of a sharp rise between 1993 and 1995, price fluctuations were small. The second one from September 2005 characterized by large fluctuations in the aluminum price. This coincides with the commodity boom driven by the industrialization of China and India (Kilian, 2009; Diaz and Perez-Quiros, 2021). We can clearly identify the effects of the 2008 global economic crisis and the Covid-19 Pandemic in 2020. Thus, the aluminum price decreased from a value of 2,957.86 dollars per ton in June 2008, to 1,330.20 in February 2009, which represents a rate of decrease of a 55% in only 9 months. Conversely, the price of the ton of aluminum was 1,466.37 in May 2020 rising sharply in the following months until it reached a historical maximum price of 3,498.37 dollars per ton.

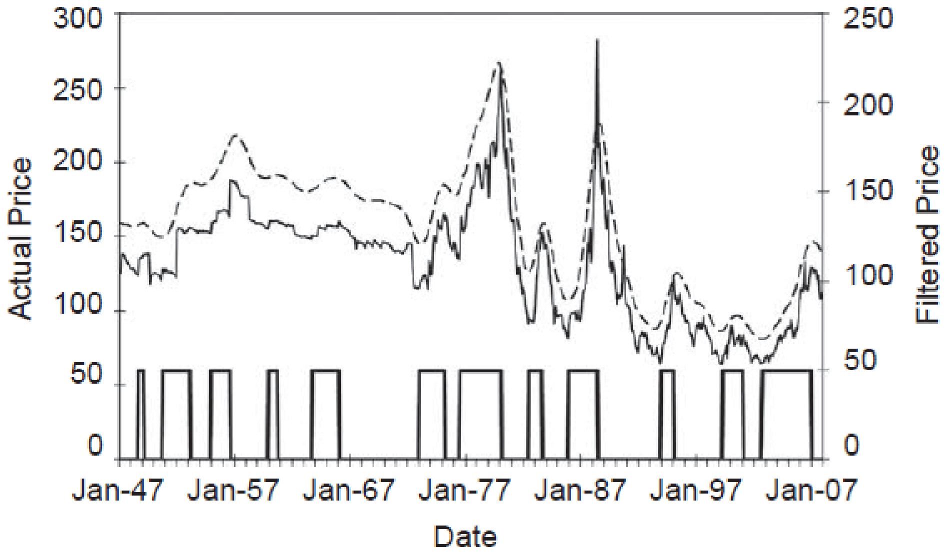
Figure 1. Evolution of nominal aluminum monthly prices from 1992 to 2020



Source: Own elaboration based on World Bank Data
Note: Aluminum 99.5% minimum purity.

Some authors, such as Cashin et al. (2002) researched the existence of commodity cycles, including metals. They conclude that recession phases tend to be longer than expansions phases and there is no relationship between price movements and the duration of the phases. Roberts et al. (2009) obtain similar results on the length difference in both phases of the cycle but point out that there is no relationship between price amplitude and the duration of a cycle. Furthermore, they highlight the volatility that the price experiences both upwards and downwards. In Figure 2 solid blocks at the bottom of the diagram represent the phases of the economic cycle. The block depicts the expansion phase, and the absence of a block shows the contraction phase. The beginning and the end of the block represent a trough and a peak, respectively.

Figure 2. Aluminum price and economic cycles



Source: Roberts et al. (2009)

Lesourd and Badillo (1998) go further and find that there are two types of cycles. The periodicity of the first cycle is usually less than or equal to one year, while the frequency of the second cycle is greater than one year. These conclusions have been reached using Weibull tests and a structural time series method. It should be noted that these price analyses refer to the cost of pure aluminum. But within all aluminum alloys there can be a wide range of prices depending on the alloying agents used and the cost of the chemical and mechanical processes employed.

In addition to studying the price of aluminum, its relevant to take into account the price of other goods to get a more general view of how the cost of metals fluctuates and, whether there is a correlation between all of them. According to the data in Table 3, it can be noted that metals and minerals have common trends.

On the one hand, there were no price variations of more than 17% in any of the metals considered from 2019 to 2020. On the other hand, by 2021, all prices increased sharply over the first two four-month periods compared to the average of the previous year, with rises of up to 90.73% in the case of aluminum, and even 152.51% in the case of tin. This evolution of the prices of all metals over the years shows that they are highly correlated. It would therefore be desirable to consider the general trend of all metals when analyzing the aluminum market.

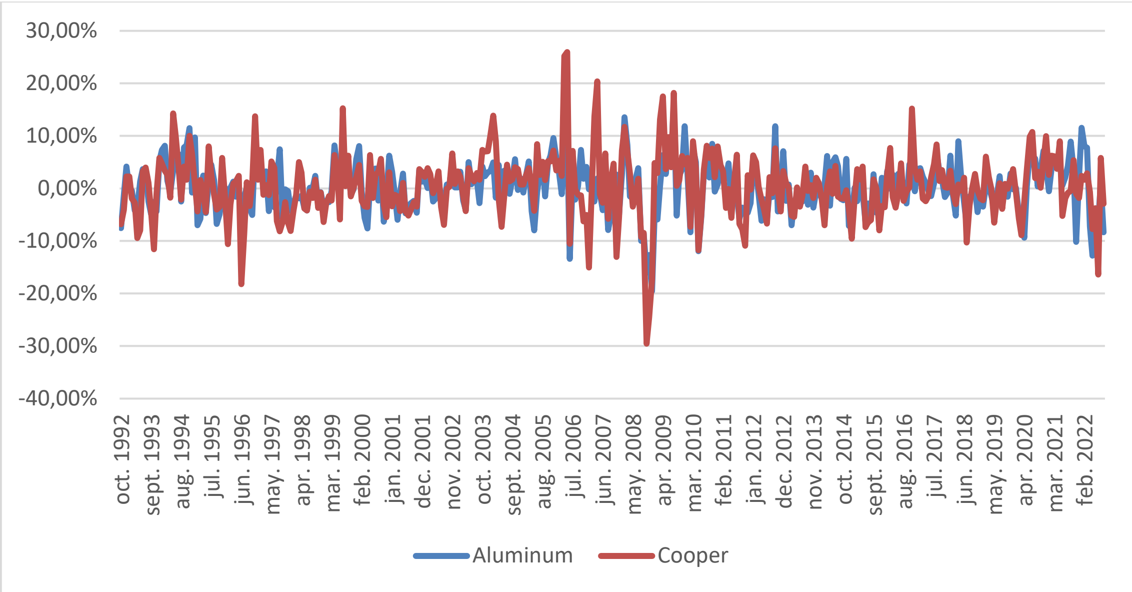
Table 3. Commodity price comparation over the last 3 years.

			Annual Averages			**Quarterly Averages**					**Monthly Averages**		
			Jan-Dec	Jan-Dec	Jan-Dec	Jul-Sep	Oct-Dec	Jan-Mar	Apr-Jun	Jul-Sep	Jul	Aug	Sep
Commodity	Unit		2019	2020	2021	2021	2021	2022	2022	2022	2022	2022	2022
Metals and Minerals													
Aluminum	$/mt	b/	1,794	1,704	2,473	2,645	2,755	3,250	2,879	2,356	2,408	2,431	2,228
Copper	$/mt	b/	6,010	6,174	9,317	9,382	9,703	9,985	9,521	7,759	7,545	7,982	7,749
Iron ore	$/dmt	b/	93.8	108.9	161.7	166.9	112.0	142.5	137.7	105.7	108.6	108.9	99.8
Lead	$/mt	b/	1,997	1,825	2,200	2,333	2,326	2,325	2,196	1,975	1,985	2,073	1,868
Nickel	$/mt	b/	13,914	13,787	18,465	19,112	19,770	26,765	28,951	22,132	21,482	22,057	22,858
Tin	$/mt	b/	18,661	17,125	32,384	34,644	38,768	43,242	36,773	23,730	25,396	24,647	21,145
Zinc	$/mt	b/	2,550	2,266	3,003	2,990	3,357	3,727	3,914	3,274	3,105	3,588	3,130

Source: The World Bank (2022)

In this sense, some metals such as copper have experienced a similar price evolution to aluminum as can be seen in Figure 3. By analyzing the price variation for both metals over the last 30 years, we find a correlation coefficient of 0.657.

Figure 3. Monthly comparison between the rate of change in the price of aluminum versus the rate of change in the price of copper (Correlation coefficient: 0.657)



Source: Own elaboration based on World Bank Data

2.3 ENVIRONMENTAL IMPLICATIONS

While aluminum has many beneficial uses, the production of aluminum can have negative environmental implications. With the growing concerning about pollution when it comes to energy extraction, the recycling of some metals including aluminum has increased dramatically. With respect to aluminum, this is mainly due to two factors (Ayres, 1997). One is the improvement of inventories and specialized technologies. The other is the energy required to extract aluminum from raw materials. Extracting bauxite requires great amounts of energy and this energy is often produced by burning fossil fuels.

The energy needed to melt aluminum and recycle it from scraps is only 5% of the energy required to go through the whole process of production and extraction from the ores (Raabe, 2022). For this reason, and with electricity prices skyrocketing, companies, in addition to giving a good image with recycling and reducing the emissions of gases, have the ability to greatly reduce their costs.

Within the production of metals, aluminum is one of the biggest greenhouse gas (GHG) producers (including methane, nitrous oxides, carbon dioxide, hydrofluorocarbons and perfluorocarbons), contributing a 15% of all the GHG emissions in the industrial sector (Raabe, 2022). Nearly 20% of the total production emissions come from the production and oxidation of the carbon anodes that are used in the electrolysis, and the rest of the emissions come for the carbon used to obtain the electricity demanded during the electrolytic process (Daehn, et al. 2022).

It is possible to make aluminum more environmentally friendly as most of the emissions come from the carbon used to create electricity. One approach is to use renewable energy sources, such as solar or wind power, to produce the energy required for aluminum production. Another approach is to use more efficient production methods, which will keep improving in the future with the advancement of the technology. In addition, companies that produce aluminum can work to minimize their environmental impact through responsible waste management and conservation efforts.

In order to reduce the biggest environmental impact during the production of aluminum, the best method at the moment is integrating hydropower energy into the Bayer process, one of the first steps in refining bauxite. By changing the source of energy needed it is possible to reduce the global warming potential by approximately 33%, and the greenhouse gases emission up to a 70% (Zhu, et al. 2022). Another viable option includes using thermal power, even though it does not seem to be as efficient.

Looking into the future, and according to the International Aluminum Institute the amount of available aluminum scrap is going to increase from 37.449 kt in 2022 to 71.646 kt in 2040, and the primary ingot production from 66.061 kt to 82.854 kt (International Aluminium Institute. (n.d.). AluCycle). Based on this data it is clear to say that all the aluminum sector is expected to grow, but the secondary aluminum sector will have an exponential growth compared to the primary aluminum sector, increasing in about a 191% in the above-mentioned interval. This prediction gives a view of the importance that recycling some metals has and the potential of this sector on the market.

Not all the aluminum scrap obtained from end-of-life discarded products can be recycled and used to produce new wrought alloys. Based on a simulation model that calculates the amount of scrap that can be reutilized, by 2030, 88,6% of the scrap will be recycled for future products while the other 11,4% would constitute a surplus (Van den Eynde, et al. 2022). This model uses as limits the different percentages of the elements (Cu, Fe, Mg, Mn, Si, Zn, Other) that make up the alloy series (1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000).

Although it is not foreseen that 100% of aluminum will be recycled and it is still necessary to continue advancing in the measures and techniques to improve recycling, there have been great advancements in the last century. The first aluminum products that were sold in mass to the public were kitchen utensils and aluminum foil during the 1930s and 1940s, but it was not until the end of the 1960s that the campaigns for recycling and keeping the cities clean from trash cans and other aluminum products started (Thorsheim, 2018). Nevertheless, despite the beginning of the awareness campaigns, the big industries did not show interest in making their products in a way that would facilitate their reuse. Yet, this has been gradually changing over the years until today, where the majority of the population wants to preserve the planet and is moving towards a better and sustainable future.

Despite the environmental concerns, aluminum does have some environmental benefits. For example, it is a lightweight metal, which makes it ideal for use in vehicles and other transportation applications. This can lead to reduced fuel consumption and lower carbon dioxide emissions.

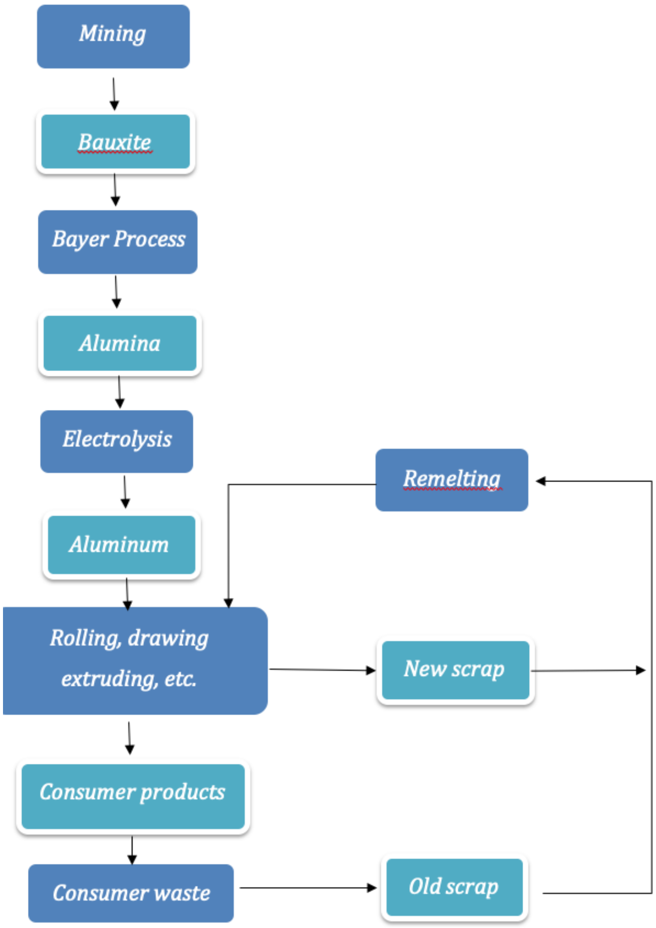
Chapter 3. SUPPLY OF ALUMINUM

3.1 PRODUCTION PROCESS

The production processes of aluminum have remained unchanged over the years although within each of these processes certain improvements in equipment have been incorporated as technology has advanced over the years. The main process used is called the Hall-Heroult process and was developed in 1886 (Boyd, 1995). This process involves dissolving alumina using a sodium cryolite melt, to produce liquid aluminum in the cathode while, on the anode, greenhouse gases and important amounts of CO_2 are produced.

There is another option to obtain aluminum which has been gaining importance the last few decades, which consists of recycling. The aluminum obtained by this method is called secondary aluminum. Climate change and the growing awareness of recycling are some of the factors that have affected the growth of this sector and have contributed to its increasing relevance today. We first describe the production process of primary aluminum and then continue to discuss the secondary aluminum industry.

Figure 4. Aluminum production process



Source: Boyd (1995)

The first step in this process is mining to obtain bauxite, which is, the main raw material used in the production of aluminum. Bauxites are residually enriched rocks consisting mainly of Al hydroxides (gibbsite, boehmite and diaspore), kaolinite, Fe hydroxides and Ti oxides. Humid, tropical, and subtropical climates are most suitable for bauxite formation (Boyd, 1995).

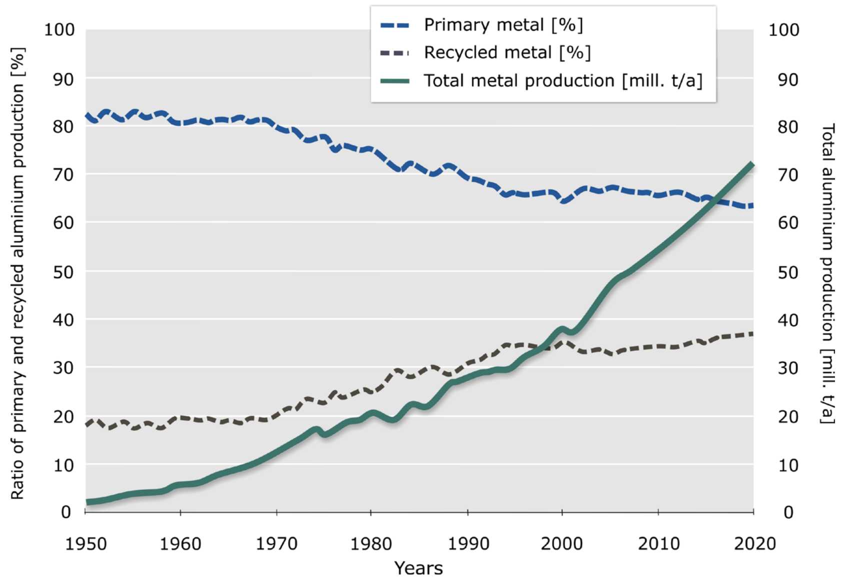
Bauxite is a type of mineral resource created under intense chemical weathering in specific zones with appropriate degrees of heat and humidity (Bogatyrev, et al. 2009). Bauxite reserves can be classified into three different types: laterite-type, to which the most common ores, with an 88% of bauxite deposits in the world, belong; karst-type with an 11,5%; and Tikhvin-type, with a 0,5% (Meyer, 2004).

In the following step, aluminum oxide is removed from the raw ores using the Bayer Process. Once the alumina is obtained, the smelters remove the oxygen by electrolysis. This last step requires a lot of electricity and is one of the most expensive operating costs to obtain aluminum. After completing these steps, aluminum is finally obtained, and then shaped by rolling, drawing, extruding or other processes for its commercialization. Ingots, sheets, etc. are delivered to the transport, construction, packing and engineering industries. The metal can also be mixed with other metals to obtain alloys or be thermally treated to change its properties. The possible alloys that can be obtained have been explained in chapter 2.1.

Conversely, in the study of aluminum products, aluminum from raw ores is as important as aluminum from scrap. Recycling aluminum from scrap is an alternative to mining, which contributes to saving resources and increasing environmental awareness. Another reason for using scrap materials, in addition to recycling, is that the energy requirements are lower, which means lower costs for companies.

Figure 4 shows the evolution of primary and secondary aluminum production from 1950 to 2020. The figure indicates a growth in the use of secondary, recycled aluminum compared to the primary metal. The main reasons for the shift between primary and secondary aluminum are the significant differences in the energy consumption and CO_2 produced.

Figure 5. Total production, primary and secondary production of aluminum



Source: Steinbach and Wellmer (2010)

Aluminum scrap receives three different denominations depending on how it is obtained: new scrap, old scrap, and home scrap (Blomberg, 2009). New scrap is obtained during the manufacturing process, from smelting to the creation of the finished goods. Examples of some new scrap could be clippings or skeletons of can lids. Almost all new scrap is recycled, as its composition is known to the factories and there are high costs of storing as opposed to recycling it.

Old scrap is obtained from used products after they finish their useful life. Some of these products are used cars and cans. To recycle old scrap metal, more processing is needed, and more intermediaries are involved in the production chain, such as scrap collectors and traders.

Home scrap is the last type of scrap and is the one obtained during smelting. It is usually reprocessed in the factory where it was produced. This type of scrap has never been transformed into any kind of product or entered the market.

Once the scrap reaches the recycling plants, after being previously shredded, different methods are used to separate aluminum from other metallic and nonmetallic residues (Padamata, 2021). Firstly, the metal is subjected to magnetic separation, where it is possible to separate the ferrous metal scrap. In this process, scrap passes close to an NdFeB magnet and materials such as iron or steel which are ferromagnetic, get attached to the magnet and are separated from the rest of the scrap.

The next process is air separation, in which light materials, such as foams or plastics are removed from the rest of the scrap. Here the scrap is pushed upwards by a flow of air. The lighter materials are pushed further while the heavy metals remain at the bottom. This has a disadvantage which is that some metal components such as foils can be mixed and confused with unwanted materials, leading to the loss of some aluminum scrap. The next step is the sink/float method, whose purpose is to separate materials of different densities. In this step, heavy metals, such as copper, zinc or magnesium, are removed from the rest of the scrap.

Finally, scrap is placed into eddy currents, which are induced by a variable magnetic field created by a rotating magnet. The different metals are pushed to different distances due to the difference in their densities and electric conductivity. In this process, the optimum parameters are, for the feed speed 0.5 m/s, the angle of detachment over 6.61º, and the ratio between the maximum cross-area of the metallic flake and the lateral area of the magnet in front of the particles between 0.08 and 0.51 (Ruan, 2017).

After all these processes, most of the unwanted materials are removed and only aluminum remains. The aluminum obtained contains several impurities that may be undesirable for the production of some products, for this reason, the metal can be subjected to several additional treatments. The method to obtain the largest purity aluminum is low-temperature electrolysis. With this method it is possible to reach aluminum with 99,9% purity, which is possible using an anodic dissolution of Al-Si alloy, having the electrode potential set to 0.3V or lower (Huan, 2020).

Another possible method is remelting and fluxing, but this one does not give as good results as the one mentioned before. The best percentage of pure aluminum that can be obtained using this process is 97%. Remelting consists of heating pure aluminum to 800ºC and mixing it with metal scrap. During the oxidation some metals like Be, Ca or Mg can be removed while others are evaporated (Zn, Hg or Cd). Flux can be added to the process to improve it, and it is a common technique used in the industry. When the aluminum is being heated in the furnace, the salt is mixed with the scrap metal. Due to the salt, some impurities such as Na, Mg, or Ca react with the salt, allowing them to be removed.

3.2 TRANSPORTATION

Aluminum is a strong and resistant material, for these reasons it is easy to transport, as long as a few precautions are taken. This includes covering the surface of the material with plastic or bubble foil, to prevent aluminum pieces from bumping between each other when moving from one place to another and causing different damages, that can go from appearance defects to structural damage, making it unusable for security reasons. Apart from the collisions, another possible damage to the material is corrosion, especially during long transportation times, so it is crucial to pay attention to the moisture levels (Proper Handling and Storage of Aluminium).

There are 3 possible transports that can be used for aluminum: by boat, truck, or rail. Normally, aluminum transportation involves more than one of these methods. As most of the aluminum comes from China, normally it is transported first by boat, until it arrives to their destination countries, and then the material is moved by truck or rail. Due to the importance of the water and the moisture conditions, combined with the waves and the possible sudden movements of ships at sea, the means of transport in which a higher level of precautions must be taken is the ship (Guide to Freight Shipping Aluminum, 2023).

Apart from the aluminum preservation methods mentioned above, and the main indicators to take into account when transporting the aluminum, as the moisture, there are other factors that can be relevant as well. One of these factors is the temperature, as the temperature control must be supervised in locations with extreme weather conditions, because aluminum is a metal really sensitive to these changes. Another moment during the transportation that can be of relevance is the loading, and it must be done carefully and, if possible, with special equipment as cranes or forklifts.

To sum up, aluminum is a material that is really easy to transport as long as a few precautions as covering the surfaces of the material are taken, and the appropriate conditions are met, including mainly the moisture and the temperature control. If all this is fulfilled there should not be any issue transporting aluminum to its destinations in optimal conditions.

3.3 EXTERNAL FACTORS THAT AFFECT THE SUPPLY OF ALUMINUM

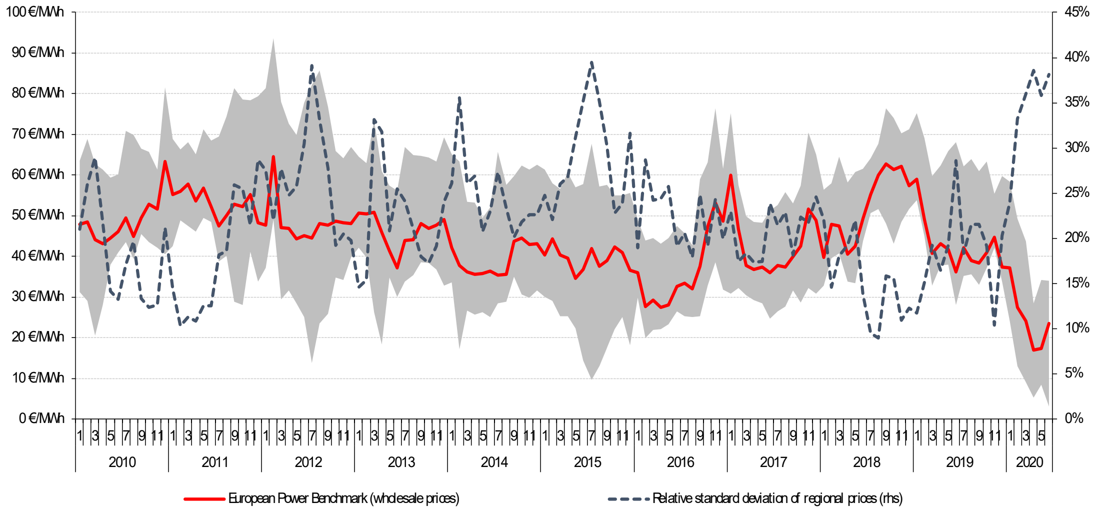
There are several factors that can affect the supply of aluminum. One major factor is the availability of raw materials. For aluminum it would be the bauxite and its supply. Since 1950, bauxite production has been increasing 5% each year, and if this trend is consistent over time, in a few decades, time bauxite reserves will be exhausted (Meyer, 2004). This possible future is seen from a pessimistic point of view, as it considers that new bauxite reserves will not be discovered which is very unlikely. Apart from the amount of bauxite that can be extracted from the reserves it is crucial to consider the geographic location of the reserves, as the geologic environment and the economic and political conditions are relevant for the accessibility to extract the necessary resources and to explore the land for new mineral reserves.

There are other several factors with large influence over the supply (Nappi, 2013):

- Higher energy prices: In 1973 and 1979, energy shocks occurred along with the emerge of energy demand on growing economies, for these reasons energy prices were pushed up, and as it has been explained previously on this paper, aluminum production requires great amounts of electricity that are derived from energy. These price increases did not happen all around the globe as some countries used other types of energy that were cheaper. This was enough to start shifting the production form countries like Japan or the United States to Australia, Canada, and China.

  As Figure 6 (using as reference the European Power Benchmark) shows, there is a close correlation between electricity and aluminum prices. From 2011 to 2016, the price of MW/h had a downward trend, where it reached a local minimum on the chart. This coincided with a minimum on the aluminum price as well (Figure 1). After that, both price indexes show an upward trend until 2018, when it reverses again, finding another minimum in the middle of 2020.

Figure 6. Evolution of wholesale electricity prices in the EU



Source: European Commision (2022)

- Arrival of new players: During the 1960s the aluminum world market was dominated by Six Majors: Alcoa, Alcan, Reynolds, Kaiser, Pechiney and Alusuisse. The following years, new private or government-influenced companies started to enter the market, controlling part of the production process, as well as the bauxite extraction.

- Exchange rates: Aluminum is a commodity based on the dollar, even though its producers and consumers are all around the world and from countries with different currencies. This implies that changes in currency pairs, can move the prices of aluminum based on the USD, even though the fundamentals of aluminum industry remain equal. Exchange rates of the currencies of countries with large aluminum exports have great relevance, having the ability to predict the price of aluminum contracts in the short term. Even countries with a minor relevance in aluminum exports, such as Australia, Canada, South Africa and New Zealand, can help predict aluminum prices (Pincheira, 2021).

- Shifting trend in aluminum cost curves: Cost curves provide information about the average operating costs in a year for the smelters, as well as helping improve the efficiency. Since the 1980s, the industry's cost curve has changed and evolved into a flatter shape due to the reduction of the difference between the minimum and maximum costs of the different companies in the sector. In addition, the cost curves have dropped due to the advancement of technology, the different energy prices, and the value of the U.S. dollar.

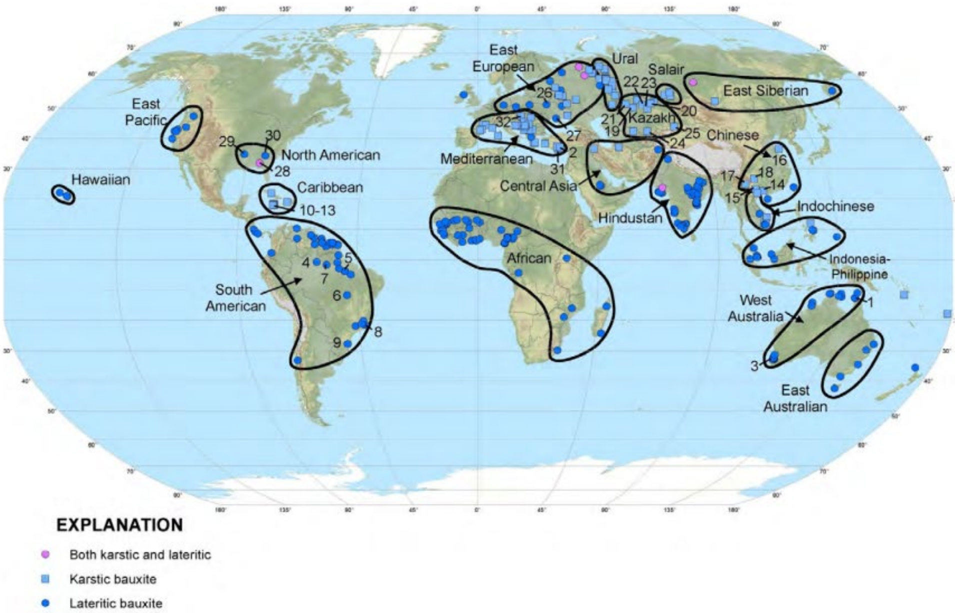
- Emerging economies: Countries like Brazil, Russia, India, or China experienced an exponential growth in GDP this last century, increasing drastically their share of primary production and consumption of aluminum with respect to the western world. As a result of these countries entering the market, there has been a significant increase in production, and this trend is expected to continue in the future.

3.4 GLOBAL SUPPLY OF ALUMINUM (ACCORDING TO COUNTRY/COMPANIES)

The countries with the largest aluminum production and exports are those with the largest bauxite reserves, as it is the principal ore for the elaboration of aluminum.

Lateritic bauxites are the most common and spread type of bauxite deposits, and the largest deposits known can be found in South American countries, especially in Venezuela, were the largest deposit, called Pijiguaos is located. On the other hand, most of the Karstic-type bauxite are located on Europe and are, in general, much smaller deposits (Schulte, 2013).

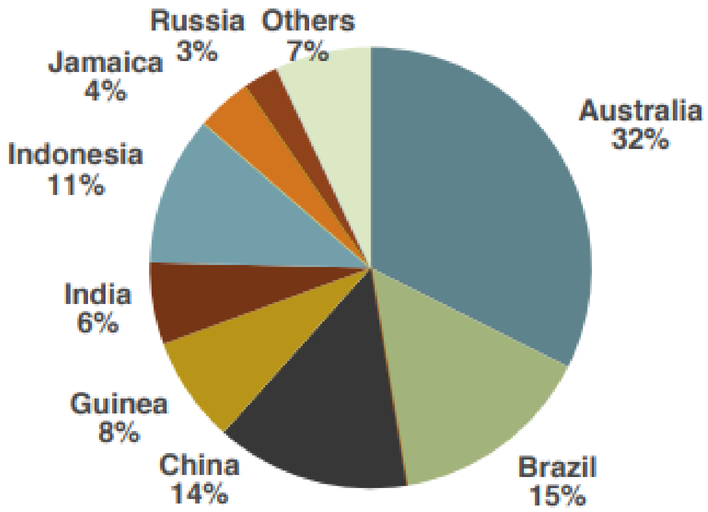
Figure 7. Bauxite Reserves around the world



Source: Schulte, 2013

Figure 8 shows that bauxite reserves are concentrated on some countries. The major producers are Australia with a 32% global share of bauxite supply, Brazil with a 15%, China with a 15% and Indonesia with a 11%. Only these four countries control over a 70%, having a great relevance on the bauxite mining sector (Nappi, 2013).

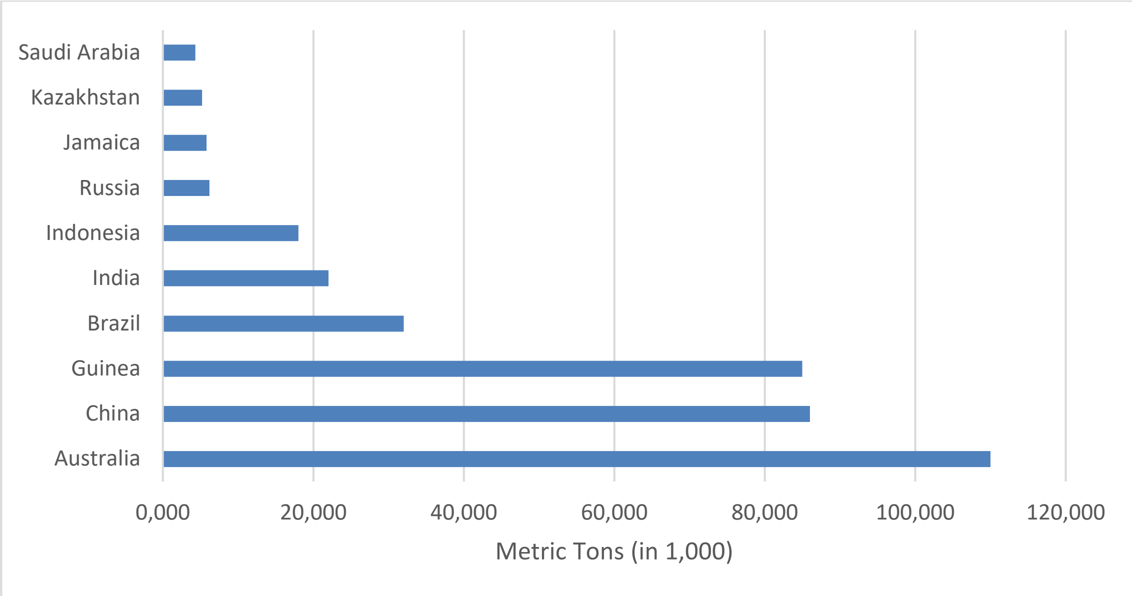
Figure 8. Distribution of World Production of Bauxite (2010)



Source: Nappi, 2013

Figure 9 shows the countries with the largest bauxite production in the World in the last year. This chart compared to the one above helps to see the evolution during the last decade of the biggest producer countries in the world, and it is clear to see how the top 4 producer countries are the same, even though the amount extracted has changed a bit. Australia is the largest producer with a production of 110 million tons in 2021. It is followed by China and Guinea with 86 and 85 million tons respectively. With lower production levels are Brazil, India and Indonesia with 32 million of production for Brazil, 22 million for India and 18 million for Indonesia. Finally, a last group of producing countries includes Russia, Jamaica, Kazakhstan and Saudi Arabia, with a production range between 6 and 4 million tons. Australia has been mining bauxite since the 1960s and is also the second producer of alumina. China is the largest producer and consumer of aluminum, and also the largest importer of bauxite with 110 million tons in 2021. The major supplier is Guinea, accounting for 52% of China´s total bauxite imports. Australia and Indonesia accounted for 31% and 15% of the imports, in 2021. Guinea is the world´s largest bauxite exporter and has the largest reserves of bauxite in the world.

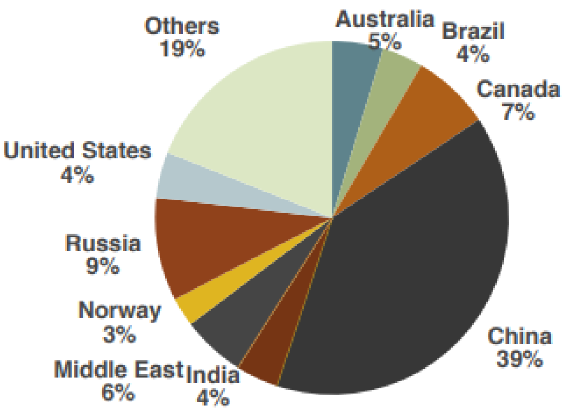
Figure 9. Major countries in worldwide bauxite mine production in 2021



Source: Own elaboration based on U.S. Geological Survey (2022)

If we focus on the aluminum production sector, the distribution of the sector is somewhat different from that of bauxite (Nappi, 2013). Since production requires large amounts of energy, the price of electricity has a huge influence. For this reason, the leading countries in this sector are those that can produce energy at lower costs. Leading this part of the market is China with a market share of 39%. China has taken the lead due to energy prices, provincial subsidies, and trade policies.

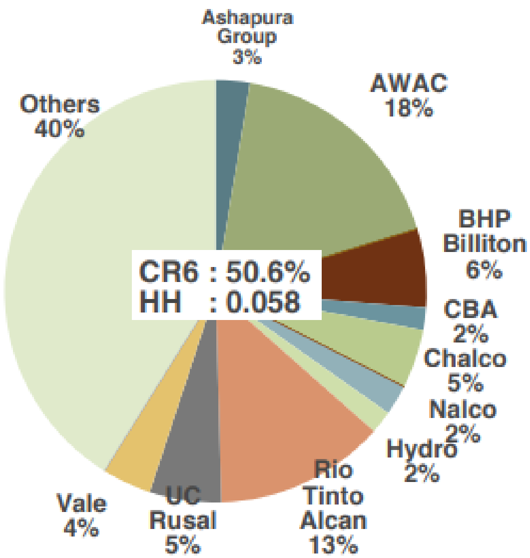
Figure 10. Distribution of World Production of Aluminum (2010)



Source: Nappi, C. 2013

With respect to companies, the Six Major companies that used dominate the market since the 1960s: Alcoa, Alcan, Reynolds, Kaiser, Pechiney and Alusuisse), started losing market share as new companies were created. In 2010, all this companies dropped their total share of the bauxite mining market to 50%.

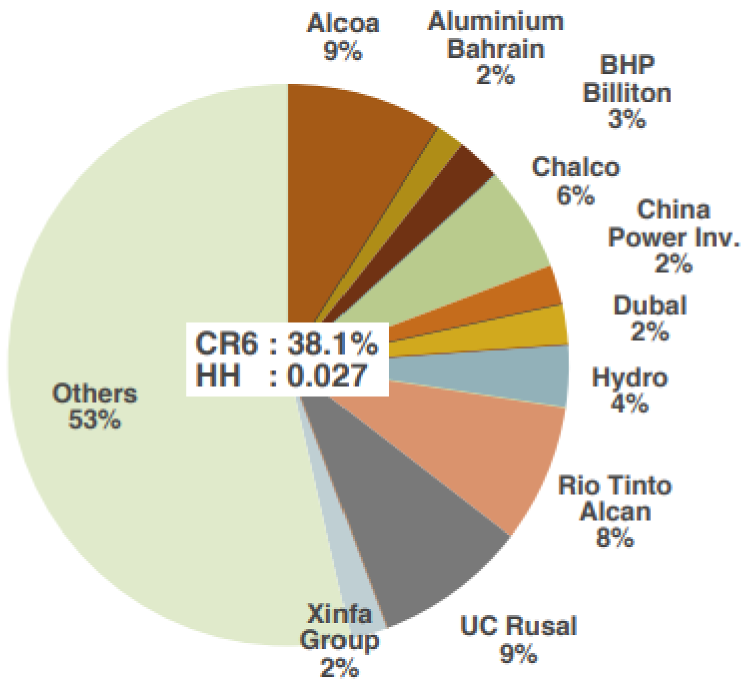
Figure 11. Market Share in Global Bauxite Capacities (2010)



Source: Nappi, C. 2013

This companies are present on the pie chart through companies they bought a share of. For example, Alcoa bought a 60% of AWAC, having as a result a 10,4% of the market share, Alcan acquired the 100% of Rio Tinto, resulting on a 13% participation on the market, and the other previous big companies (Reynolds, Kaiser, Pechiney and Alusuisse) were replaced by bigger ones: Alumina Ltd (has 40% of AWAC), Hydro, BHP Billiton, UC Rusal and Chalco.

Figure 12. Market Share in Global Primary Aluminum Capacities (2010)



Source: Nappi, 2013

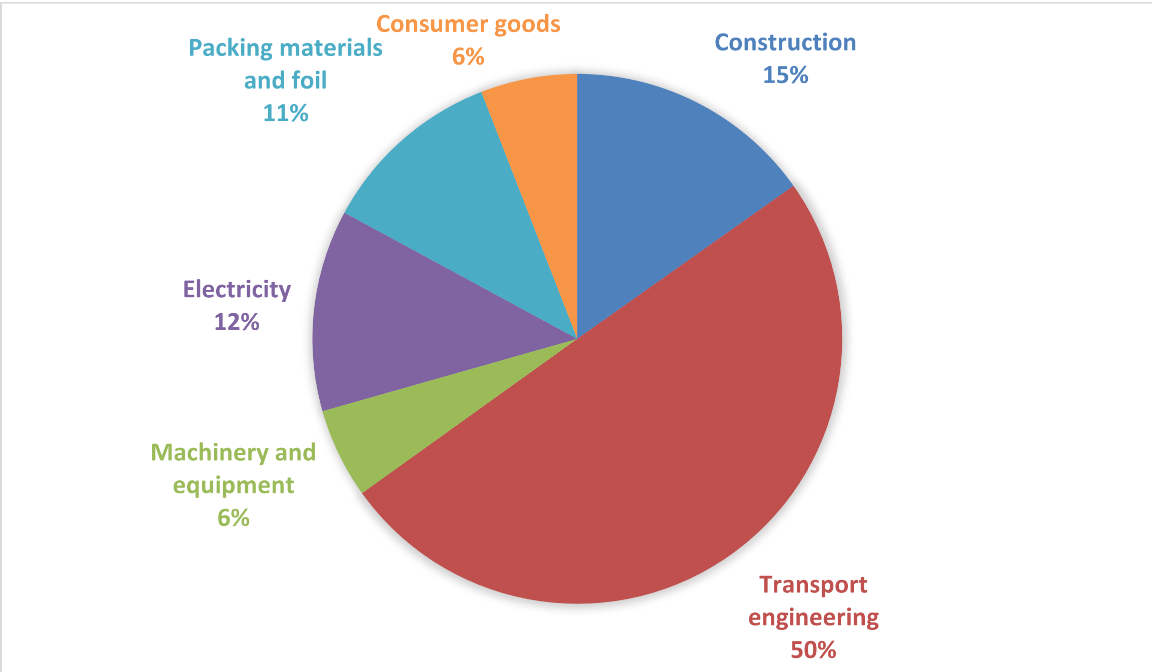
In 2010, Six Majors only conserved 38% of the market, half of what they used to have during the 1960s, resulting in a competitive market. One fact that needs to be highlighted about the companies in this sector, though, is that they do not usually focus on the entire aluminum production chain, from bauxite mining to refining to produce the metal, but only focus on a part of it.

Chapter 4. DEMAND OF ALUMINUM

4.1 USES OF ALUMINUM

Aluminum is widely used, particularly in the automotive, aeronautics and construction sectors. This is due to several factors, but the main one is the strength to weight ratio of the material. In the chart below it is possible to see how the transport engineering represents nearly a 50% of all the aluminum used as, with the use of this material, it is possible to make the car as safe as with other metals, but much lighter, increasing the acceleration, speed and drastically reducing the fuel cost.

Figure 13. Global demand for aluminum semi-products in 2015



Source: Dudin, et al. 2017

The sector that requires a higher amount of aluminum to work is the aeronautical, where 80% of aluminum is used to build aircrafts, and up to 90% in spacecrafts (Dudin, et al. 2017). The reasons are obvious given that if aircrafts were not made with such a light metal, the fuel consumptions would be unfeasible to pay for any company.

Apart from the aeronautical sector, a lot of aluminum is used on other constructions as on ships. Aluminum is used on a wide variety of vessels, particularly on high-speed vessels, due to the low weight of the material. On this type of construction, the aluminum alloy used is really important, given that the metal suffers greatly from fatigue from the continuous movement as ships are not structures that remain stationary, and the metal can be corroded easily by being in contact with seawater for a long period of time. For these reasons, some vessels built with aluminum in the past had several structural problems, and at the moment, it was concluded that the 5xxx-series were one of the best for their excellent corrosion resistance (Sielski, 2007).

With regards to the packing materials and foil, aluminum is the material used par excellence, thanks to its great recyclability compared to plastics and the ease with which it can be adapted to the food to be wrapped inside it. Another reason that makes it unique is its high degree of barrier protection, as it keeps the food separate from the moisture, light and oxygen, using a very thin sheet of material (Green, 2020).

If we think of the electrical sector, at first glance it may seem that aluminum is not widely used, because its conductivity is $37.8 \times 106\ S{\cdot}m^{-1}$, while that of other materials such as copper is $59.6 \times 106\ S{\cdot}m^{-1}$, which is almost twice as high. But the reality is not so, and in many aspects, it is more efficient and cost-effective to use aluminum even though it conducts current more poorly. This is because although aluminum has only 60% of the conductivity of copper, its weight is 30% of that of copper (Gomez, 2018). That means that a bare aluminum wire weighs half as much as a copper wire with the same electrical resistance. For this reason, the cables that hang from the power lines are made of aluminum because, when hanging and being such big cables, the weight plays a fundamental role (Kimsen, 2022).

Also, aluminum is widely utilized in consumer goods and machinery across many industries because of its lightweight nature, strength, resistance to corrosion, thermal conductivity, and electrical conductivity. There is a great variety of products made with aluminum on the market. Some examples are laptops (electronics), smartphones (electronics), refrigerators (appliances), pans (cookware), wheels (automotive industry), ladders (construction equipment), etc.

4.2 EXTERNAL FACTORS THAT AFFECT THE DEMAND OF ALUMINUM (E.G DOLLAR)

One key factor affecting the demand of aluminum is the level of industrial production based on this metal. The production is expected to increase in the construction, transportation, packaging, and electrical industries.

Transportation is poised to witness substantial expansion in the forthcoming decade, emerging as one of the most rapidly advancing sectors. Forecasts indicate a projected growth of aluminum demand from the transport sector ranging between 19.9 Mt and 31.7 Mt, primarily propelled by the adoption of electric vehicles (CRU International Limited, 2022). This shift towards electric mobility requires the utilization of significantly higher quantities of aluminum due to their construction involving substantial battery systems instead of traditional combustion engines.

Other industrial sectors are also poised for growth, driven by distinct factors. The packaging will expand due to the rising popularity of can drinks and the shift in the Chinese market from glass to aluminum beer containers. Meanwhile, the construction sector is expected to experience growth for the escalated demand of buildings specially in Asia and China. Furthermore, the electrical sector will witness an upsurge for the implementation of low CO_2 policies, as aluminum is more environmentally friendly and easier to recycle than copper (CRU International Limited, 2022).

One more factor to take into account is the global economic and political situation. Tension due to wars in certain countries, added to the economic pessimism around the world influences the markets and the demand of most of the commodities including aluminum. Specifically, the tighter global monetary policy, dollar´s strength and the property crisis in China have pressured the aluminum market downwards the last months (Manthey, 2022).

Another crucial consideration is the impact of pricing dynamics on the demand for aluminum. Shortages of aluminum supply can increase the price having a negative effect on the demand. Particularly, cost-sensitive industries that are heavily reliant on aluminum, may experience a decrease in demand, as manufacturers will try to look for alternative materials to create their products, contributing to the potential reduction in the demand for aluminum.

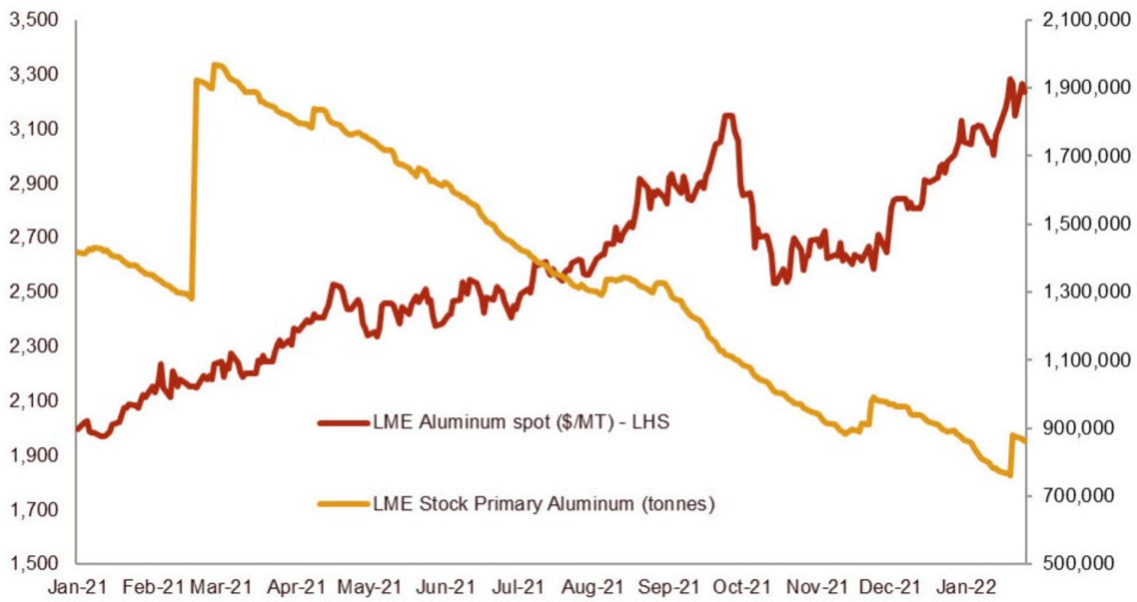
4.3 GLOBAL DEMAND OF ALUMINUM (ACCORDING TO USE AND ACCORDING TO COUNTRY)

Over the past decade, China has been the leading consumer country of aluminum around the world, primarily due to its industrial activity as the largest global manufacturer with a wide range of products. With its significant industrial output, China has played an important role shaping the demand of the aluminum market. In 2017 it had nearly 50% of the global consumption of aluminum, followed by Europe with a 16%, and Asia and Oceania with a similar share of 16%. North America followed with a consumption of 12%. Other countries collectively constituted less than a 10% (Dudin, 2017).

Nearly 30% of China´s aluminum consumption in 2020 was used in the construction of new buildings and factories. Other sectors like Transportation, and Equipment, represent a 16% and 14% respectively. The country is expected to keep growing its aluminum demand on the next years, mainly on the transportation sector driven by the growing popularity of electric vehicles, but also for the increase of production on the machinery and equipment sector and for the installation of renewable energy plants that use a large amount of aluminum for both the structure and the wiring (CRU International Limited, 2022).

In Europe, aluminum is experimenting a high demand compared to the amount of current production. This difference on the levels of demand and supply is pushing the prices up, and even though this may seem beneficial and cost-effective for the producing companies, many of them are having trouble to stay profitable for the high costs of gas and electricity of the lasts year. From 2020 to 2021 gas prices increased nearly a 550%, which is closely related to conflicts such as the war between Ukraine and Russia, and has triggered price spikes that have a negative impact on all industries that rely heavily on energy (Depreter, 2022).

Figure 14. Primary aluminum stock in Europe



Source: Depreter, 2022

Due to current energy costs many factories have had to close, such as the primary aluminum smelter of Alcoa in Spain. While other factories are still in operation, their capacity has been drastically reduced to less than half of what it was before, such as the Alro smelter in Romania and the Slovalco smelter in Slovakia. All this changes in production summed up to the growing demand, has caused primary aluminum stocks to shrink rapidly.

In Europe, the automotive sector is the strongest one, using great amounts of lower carbon aluminum, especially for electric cars. However, not only the demand for electric vehicles has increased, but also for combustion vehicles. During Covid-19, car production decreased drastically, but now it is starting to be similar to the prepandemic levels, despite the fact that full recovery has not yet been achieved (Bone, 2023). The European aluminum producer AMAG shared some data reports from 2022, where shipments of aluminum had a great growth: automotive equipment increased a 19% (4000 tons), foil stock a 18% (6000 tons) and aircrafts a 10% (7000 tons).

In North America, as in Europe, the leading sector in the demand of aluminum is transportation with a 35% of aluminum consumption followed by packaging with a 17% and construction with a 12.3% (Yi, 2022). In North America, the packaging sector consumes more aluminum than the construction sector, making it the only developed region where this is the case.

In Asia, the biggest demand growth will come from India, Japan, and the Middle East. In India and the Middle East, this will be greatly influenced by the construction and the population growth whereas, in Japan, the aluminum consumption comes mainly from the manufacturing sector. The aluminum consumption growth on some of these countries is specially correlated to the implementation of renewable energies. In India, most of the increase in consumption is due to this, and the aluminum used on renewable plants is used on the electrical sector (CRU International Limited, 2022).

Chapter 5. MODELLING THE MARKET FOR ALUMINUM

Based on the economic models previously developed, in this section we will analyze the effects of the variables considered potentially more relevant for the determination of the price of aluminum, using monthly data series from January 2002 to March 2023, the latest data available to date. All variables have been considered in interannual logarithmic form in order to linearize the relationships between variables and to obtain a better estimation and interpretation of the results. With the aim of eliminating the effect of inflation on the time series, aluminum and oil prices have been deflated to obtain real values for these series.

5.1 INDICATORS

Regarding the indicators used in the analysis, the following have been considered: Stocks, Industrial production, Construction, Transportation, Electricity, U.S. dollar (USD) and Crude Oil. Industrial production is the monthly World Industrial Production (WIP) index obtained from Baumeister and Hamilton (2019). Global construction and transportation indices were obtained from Factset. The USD and aluminum inventories are obtained from Board of Governors of the Federal Reserve System (US). Electricity data have been obtained from the Bureau of Labor Staristics (Consumer price index for all urban consumers: Electricity in U.S). Aluminum price and crude oil price are from The World Bank (2023), Commodity prices "Pink Sheet" Data.

5.2 HISTORICAL DECOMPOSITION OF THE PRICE OF ALUMINUM

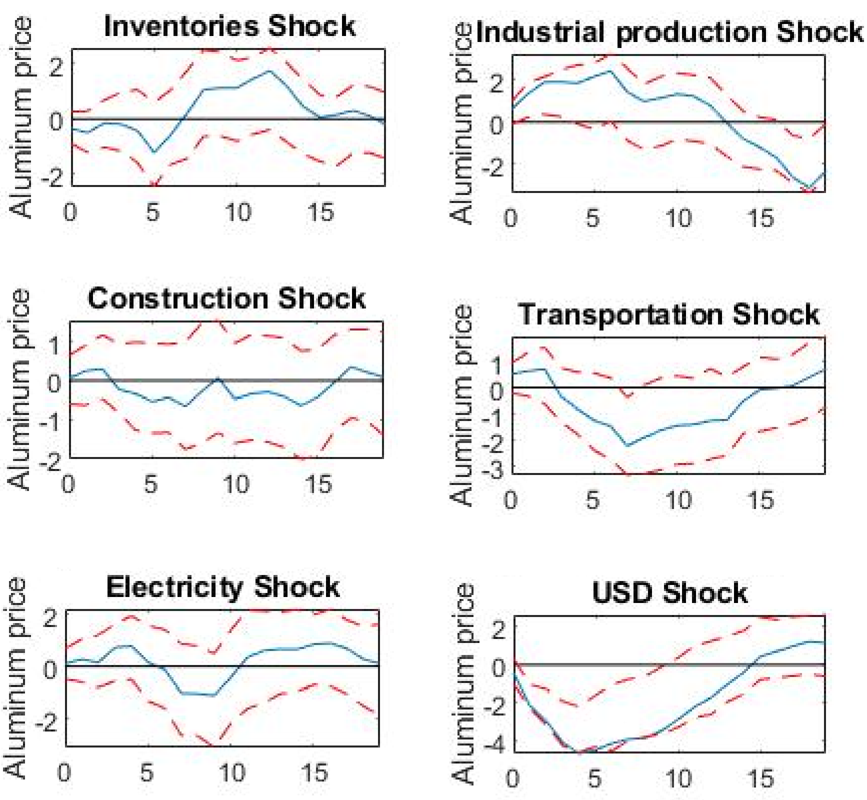
Impulse response function analyses and a historical decomposition of the price of aluminum are performed using time series data and estimating Vector Autoregression (VAR) model.

Figure 15 presents the results obtained in the estimations taking into account the variables previously related (Inventories, Industrial Production, Construction, Transportation, Electricity, USD and Aluminum). According to these results, the USD has the strongest and most significant effect on aluminum prices, showing a negative and persistent relationship over time. Because aluminum is globally traded in USD, for non-USD importers, the appreciation of the dollar increases the domestic cost of aluminum, which in turns, decreases its demand, generating the observed decrease in prices.

Industrial production also has a strong effect in determining the price of aluminum, although with the opposite sign, showing a positive relationship. The level of industrial production can, therefore, be identified as a significant indicator of demand for aluminum.

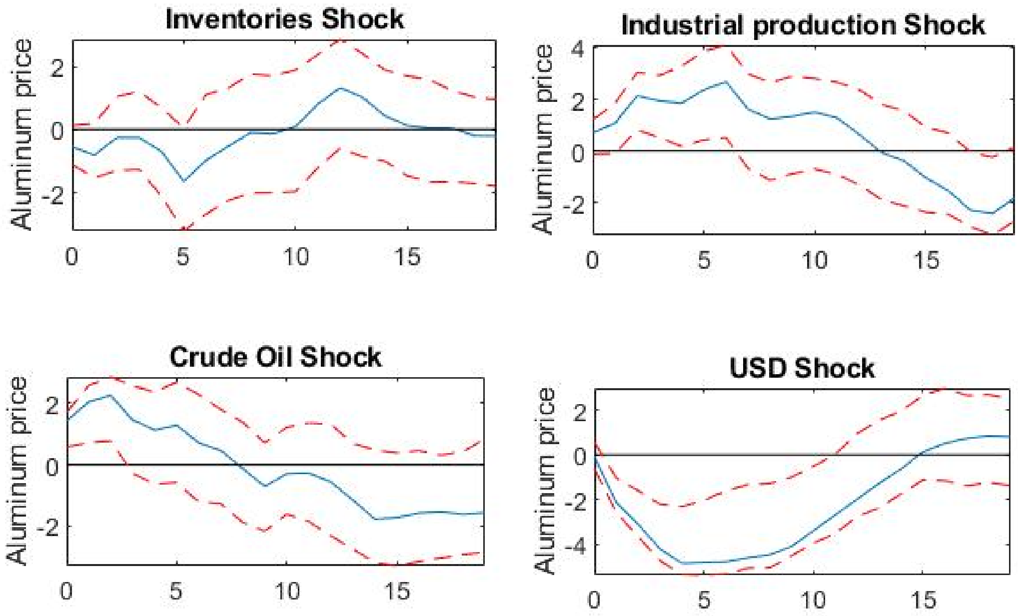
On the other hand, supply shocks, reflected in inventory changes and changes in the price of electricity, do not seem to have a significant effect on the price of aluminum. This is also true for transportation and construction, which were expected to reflect changes in demand for aluminum but are proven to be non-significant. This suggests that industrial production activity as a whole is able to account for the largest proportion of aluminum price fluctuations, including those that may be reflected in the transport and construction sectors.

Figure 15. Impulse-Response analysis 7 variables



The model is reestimated, by removing electricity, transportation, and construction, and introducing the crude oil variable. This results in a significant effect of oil prices in the price of aluminum (Figure 16).

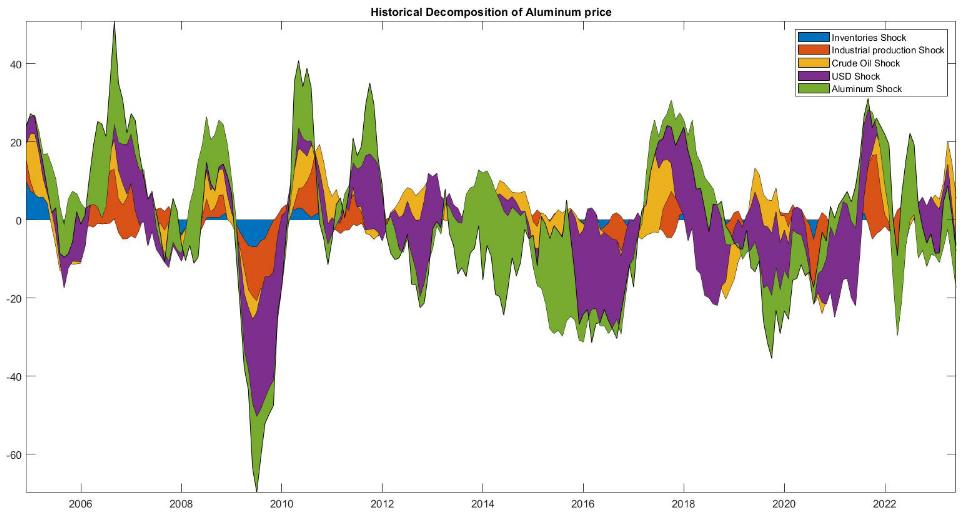
Figure 16. Impulse-Response analysis 5 variables



Results from Figure 16 show that an increase in the price of crude oil, that cannot be explained by changes in industrial activity, results in a significant increase in the price of aluminum. Notedly, this is to be expected, as energy is an important input for both the production, as well as the transportation, process of aluminum.

To complete the analysis, as can be seen in Figure 17, a historical decomposition of aluminum prices in terms of the variables that have been found to be representative in the previous functions have been carried out, to identify the causes of fluctuations in the price of aluminum during the sample of study.

Figure 17. Historical Decomposition of Aluminum price 2002-2023



The most relevant contribution made by the variables analyzed is due to the USD shock, while Inventory shocks are hardly visible in the Figure 17, as expected according to the results obtained in previous estimations from the VAR model. Some years are particularly relevant, as can be seen from 2008 and 2009 onwards, the most affected years by the global financial crisis. Thus, in coincidence with this economic crisis, there was a sharp fall in aluminum prices. Although it can be explained, in part, by the reduction in industrial activity worldwide, as the crisis spread throughout the world, is further affected by the appreciation of the dollar in the recovery of the US economy.

Between 2013 and 2016 it is not possible to explain the price fluctuations based on the model variables. Between 2014 and 2016 there was a downward movement in the price of aluminum. One reason that could explain this price movement is the crisis and slowdown of the Chinese economy. As China is one of the largest consumers of aluminum, this economic situation had an impact on the price. Another possible reason is the strength of the U.S. dollar relative to other currencies. As aluminum is mainly traded in USD, for importers with a different currency, they see a price increase, reducing demand and therefore prices.

From 2016 onwards, price growth is mainly explained by an increase in industrial activity. This is coinciding with the commodity boom, in which commodity prices rose significantly due to the industrialization of China and India.

The year 2020 is marked by the COVID-19 pandemic that negatively impacted on economies around the world. The disease and the containment measures adopted to combat it led to a global economic slowdown. The GDP of world economies fell by 3.5% on average in 2020 (International Monetary Fund, 2021). However, according to Figure 17, the fall in the price of aluminum is explained rather by the change in the value of the USD than by the fall in industrial activity. This suggests that the public assistance programs implemented by most governments (Next Generation program in Europe), and monetary policy measures were more of a driver of prices than economic activity itself. As can be seen, this does not occur in the same way in the subsequent years of economic recovery, where the rise in aluminum prices is caused mainly by the growth of industrial activity.

As can be seen in Figure 17, the variations in the price of aluminum analyzed in recent years are mainly due to external factors. Since February 2022, an unplanned war in Ukraine introduced undesirable uncertainty and worsened economic trends. Disruptions in the energy (gas and oil) and other commodity markets had a significant impact on price increases, resulting in high uncertainty in international markets. Thus, in the first months since the beginning of the war metal prices reached record levels. Russia is one of the largest aluminum producers, so due to the sanctions imposed there was a significant restriction of its supply. However, while the prices of energy raw materials continued to rise, the prices of metals such as copper and aluminum, which rose at the beginning of the conflict, subsequently suffered a significant fall, probably due to the fact that, in the event of a possible lack of stock, caused by the war, there was an over-supply. This drop in prices has been gradually softening.

Chapter 6. CONCLUSIONS

Aluminum is a versatile metal with a great relevance on several industries around the world due to its properties, such as its strength/weight ratio, its thermal and electrical conductivity, or its ability to withstand corrosion. Throughout history, the price of aluminum has experienced fluctuations due to several factors, some which are supply and demand dynamics, i.e., the economic conditions, and the production costs.

Aluminum is an environmentally friendly material as it is easy to recycle, given that the most environmentally aggressive phase of production is its extraction. Nevertheless, progress is being made to reduce the footprint and the greenhouse gas emissions of this phase during the refining process of the metal.

Examining the supply side, a wide number of external factors can have an influence on aluminum price, including government regulations, energy prices, geopolitical events and technological advancements that can improve the efficiency of the bauxite extraction or contribute to optimize the energetical costs.

On the demand side, aluminum is present in various sectors, including construction, transportation, packaging, and electrical engineering, being the most important one the transportation, as every vehicle contains aluminum parts. In particular aircrafts have at least a 50% of its weight made with aluminum. Other factors mentioned on this project that play a role in the demand are the exchange rates and trade policies.

In this project we have analyzed the effects of different variables that were considered potentially relevant from an economic point of view, on the aluminum price. For this purpose, impulse response functions and historical decompositions from 2002 to 2023 have been estimated. The results obtained show a relevant negative effect of USD variable on the price of aluminum, and a significantly positive effect of industrial production activity and crude oil prices. On the other hand, variables such as Electricity, Transportation and Construction were not proven to have any significant effect on the aluminum price.

In conclusion, understanding the dynamics of the aluminum market is a relevant issue for stakeholders in the industry. By comprehending the historical price fluctuations, environmental implications, supply and demand factors, and market modeling techniques, industry participants can have a greater knowledge of the aluminum market and can be able to adapt to changing conditions, ensuring sustainable growth and development.

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