Mytilineos "Bauxite to Aluminium" Production, an Example of Competitiveness Longevity

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Abstract

Greenfield aluminium smelters require a huge construction investment capital. Ensuring competitive energy and alumina costs, over a reasonable period of time, is also a prerequisite condition for such a smelter project, but even in this case the project payback period is long. During this time, the initial situation often changes dramatically. New market, environmental, geopolitical, social, or technological conditions, may affect the viability of the smelter and lead to an early closure. However, some old smelters are demonstrating that competitiveness longevity is possible.

Mytilineos' integrated "bauxite to aluminium" production, is such an interesting case. It has preserved its competitiveness over more than 5 decades and is facing with optimism the current challenges of the European aluminium industry. This keynote is intended to explain the achievement of such competitiveness longevity, by describing how:

- Successive operational improvements, environmental solutions, product developments, production capacity creeping and technology updates, were made over the decades without any major structural replacement such as the replacement of the busbars in the potlines.
- The alumina production equipment and processes have been progressively updated.
- The overall competitiveness of the chain "bauxite to aluminium" has been enhanced through continuous improvement (C.I.) actions and successive cost cutting projects.
- The energy and CO_2 footprint issues are being addressed by Mytilineos.

Three people related factors have been crucial in this long journey:

- The engagement of the whole workforce in C.I. processes.
- The technological awareness of the management and its capability of developing tailored projects allowing to introduce production capacity creeping and technology updates, at a minimum investment cost.
- The buildup of the shareholders' trust to the capacity of the organization and its commitment, to systematically deliver the operational and project objectives.

Keywords: Mytilineos, Aluminium of Greece, Bauxite to aluminium, Smelter life duration, Competitiveness of aluminium smelters.

1. Aluminium of Greece (AOG) Today

AOG, the bauxite to aluminium production activity, is managed by the Mytilineos' Metallurgy Business Unit (BU), one of the four top performing Mytilineos' BUs:

- Metallurgy BU:
  - Vertically integrated aluminium producer, from mine to port, with on-site combined heat and power (CHP) power plant.
  - Growing presence in recycled aluminium.
- Power & Gas BU:
  - Leading independent power producer and supplier in Greece in a growing phase.

    - High quality thermal and renewable energy sources (RES) generation capacity aiming at exceeding 2.3 GW.
    - Largest domestic private natural gas importer, consumer and exporter.
- RSD BU (Renewables & Storage Development):
    - Among the most competitive Solar photovoltaic (PV) developers and constructors in the world.
    - Reliable solutions across the lifecycle of solar projects.
    - Solar Build-Operate-Transfer (BOT) platform.
- SES BU (Sustainable Engineering Solutions):
    - Dynamic development of Sustainability Projects.
    - Implementation of new technologies on energy projects.
    - Unique know-how, strong execution track-record in power & infrastructure projects.
    - Energy turn-key thermal projects.

The existence of internal highly experienced resources and exceptional project implementation capabilities, within the wide range of the Mytilineos' activities, is valuable to AOG in two ways.

- On the one hand, there is a creative energy strategy transformed into high-efficiency power plants, renewables development, sustainability projects and effective gas trading.
- On the other hand, there are central company functions providing effective support, including proven risk-hedging performance and strong legal and regulatory expertise.

The internal synergies and AOG's support, have been enhanced since 2017, when MYTILINEOS merged its major subsidiaries, including AOG, into a new single business entity.

1.1 AOG's Assets and Operations

AOG's assets include:

- The Delphi-Distomon bauxite mines.
- The AOG alumina refinery & smelting plant.
- The CHP power plant, adjacent to the alumina refinery & smelting plant.
- The EPALME secondary aluminium production facility located at Inofyta, 70 km away from the AOG plant.
- Aspra Spitia the "home city" of AOG employees, a residential community of around 3,000 people, located in an area of 61 hectares at the Antikyra Cove, 6 km away from the AOG plant.

The main AOG's operations and volumes, are:

- Bauxite mining – Delphi Distomon:
    - Bauxite production of 0.6 million t/y.
- Alumina refining and smelting – AOG plant:
    - Alumina production of 865 kt/y of which 150-200 kt/y non-calcined.
    - Exports of alumina representing around 60 % of the total production.
    - Primary aluminium production of 185 kt/y and 15 kt/y remelting aluminium production from post-production scrap, billets representing 62 % of the total.
    - Exports of aluminium products representing around 60 % of the total production.
    - On-site port facilities providing for vessels up to 45 kt.
- Recycling - EPALME:
    - Production of 50 kt/y of billets, using post-consumer scrap and molten primary aluminium from the AOG plant.

1.2 The Greek Bauxite Deposits

Economically viable Greek bauxite deposits are mainly located around Amphisa /Phocis, close to the Itea Port on the Gulf of Corinth. Produced bauxite is transported directly from the mines to the AOG plant by truck or is shipped to AOG from Itea.

1.3 The AOG Plant

The AOG plant, with its on-site port, is well located close to bauxite mines and with access to good quality underground water. It is well integrated in its physical environment and is not visible from any urban location at a distance of less than 4 km.

Mytilineos has installed a 1 600 MW Power Generation Park adjacent to the AOG plant. AOG relies on 2 of the 3 power plants installed in the Park:

- A 334 MW "High-Efficiency CHP" using natural gas, delivering 200 MW thermal power capacity to the alumina refinery. The electrical power is sold to the wholesale market.
- A brand new "H-Type" 826 MW Combined Cycle Gas Turbine (CCGT) power plant with an efficiency of more than 63 %, capable of complementing the growing electrical supply provided by RES for covering the needs of the AOG plant from 2024, as planned in the path to Net Zero by 2050.

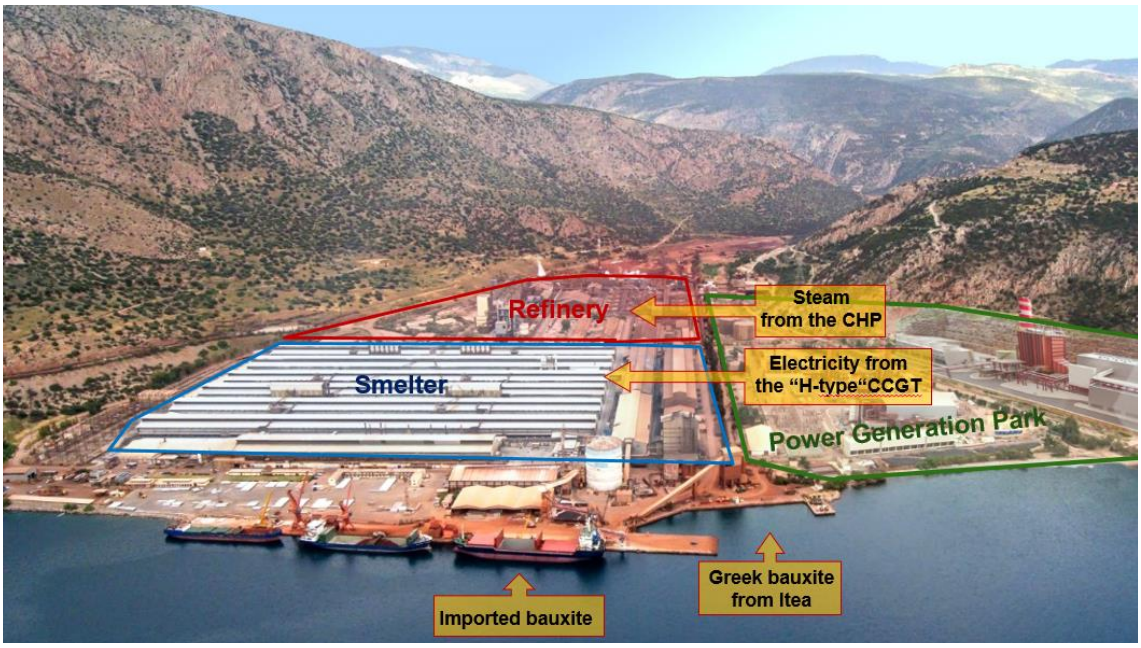

Figure 1. AOG alumina refinery, smelter and power generation park.

The technical state of the AOG plant is excellent:

- The alumina refinery is using state-of-the-art technology with modern production and waste management equipment, fully automatic process monitoring and predictive maintenance.
- After the recent major repair of the anode baking furnace, the anode plant is also in excellent condition.
- Despite the age of the potrooms and the small size of the pots, the smelting process is using modern technology and innovative digitalized pot control.
- The casthouse is using state-of-the-art technology producing high quality products.

As far as Environmental, Social and Governance (ESG) is concerned, AOG's top performance in health & safety, people management and environmental responsibility is widely recognized and has been awarded for Health and Safety actions in 2017, 2018 and 2020, for Change Management Strategy in 2019 and for research on Rare Earth Recovery from bauxite residue in 2019.

AOG is certified ISO: 45001, 14001, 9001 and 7025, as well as ASI Performance Standard.

To achieve the current state of AOG plant, after 55 years of operation, a total amount exceeding 600 million Euros has been invested in projects aiming at upgrading technology, improving operational performance and complying with tightening environmental regulations.

Investing capability has been a necessary but not sufficient condition for preserving AOG's competitiveness. In the following sections, this paper will present how AOG has demonstrated a capacity of smart investing in tailored made projects, of involving all its employees in Continuous Improvement (C.I.) processes and of effective cost cutting whenever required.

For a better understanding, it is helpful to start by shortly describing the beginning of AOG.

2. The Beginning of the AOG

The construction of the AOG plant by Pechiney started in 1963. Production started in 1966 and reached the full initial capacity of 200 kt/y of alumina and 72 kt/y of aluminium, in 1967.

At that time, AOG did not own any bauxite concessions. Bauxite was supplied on the basis of long-term contracts with Greek mining companies that had been exporting bauxite well before the construction of the AOG plant.

Electricity was supplied by the state-owned Public Power Corporation (PPC) on the basis of a 40-year supply contract. This contract had enabled PPC to finance, by the World Bank, a major dam construction project that made a step change in electricity generation in Greece.

Good quality process water was found underground. The red mud was disposed into the sea at a distance of 2.5 km from the shore and a depth of 200 m. At that point, the seafloor had a steep slope towards much deeper areas of the Gulf of Corinth.

2.1 Initial Alumina Refining Technology

The alumina refinery had been designed with a single production line. The Pechiney technology package had evolved to overcome two hurdles relating to the quality of the diasporic Greek bauxite:

- Its extreme hardness requiring the development of special crushing and grinding equipment.
- The stability of its tri-hydrate alumina content, requiring the development of equipment ensuring digestion at very high temperature and pressure.

A third hurdle, identified later, was the progressive formation of scale within the pipes and the equipment of the Bayer process due to the relatively high calcium carbonate content of the Greek bauxite. As a result, the alumina production was progressively affected by frequent stoppages for removing the scale. The problem was ultimately solved in the 90s by installing a Greek bauxite beneficiation process.

2.2 Initial Smelting Technology

The smelter design included a prebaked anode plant, two 65 kA potlines and a casthouse equipped for producing billets and slabs. The potlines had been designed with the technology then used in the smelter of L'Argentière/ Hautes Alpes/France:

- Each potline included 208 pots connected in series, in a side-by-side configuration. The pots of each potline were equally spread into two parallel potrooms. From the operational point of view, each group of 26 pots formed a working section under the responsibility of a pot operator in every shift.
- The pots were not hooded, there was no treatment of the pot gas emissions and the natural ventilation of the potrooms was insured by open sidewalls and roof openings.
- Each pot was containing 12 pairs of anodes. Every group of 26 pots was served for anode feeding, anode changing, metal tapping and anode beam raising, by a multitask overhead crane equipped with a crust breaker, an alumina silo and feeder, an anode rod holder and a heavy weight lifting device.
- There was no cabin for the crane operator. There was only a seat with control buttons, close to the floor level. The alumina feeding of the pots was done periodically, associated with lateral crust breaking. The spent anode butts were manually cleaned on the side of the pot by the operator using a long metal bar, while the anode was suspended from the anode rod holder of the overhead crane.
- In the first two years of operation, the only automatic pot control was the anode beam vertical position controlling the voltage of each pot. The motion commands were delivered by a centralized modular, hard-wired sequential logic system.
- The anode effects were treated manually. The operator was warned by a red lamp, switch on automatically on each pot, that an overvoltage had occurred. He had to introduce wooden poles into the molten bath to depolarize the anodes. Then he had to use the overhead crane for lateral crust breaking and alumina feeding and finally switch off manually the warning red lamp.
- An alternative method to depolarize the anodes was practiced later, using a tube blowing air into the bath, until the introduction, in 1968, of the automatic anode depolarization through repetitive up and down movements of the anode beam.

Figure 2. Alumina feeding in the 1960s.

3. Outline of AOG's Path to Competitiveness Longevity

What makes AOG an interesting case study is that, after 55 years of operation, the plant remains in good shape and competitive. What makes the case even more interesting, is the fact that:

- In the alumina refinery, most of the initial crushing and grinding equipment, the high-pressure digestion tanks, the clarification tanks and filters and the precipitation tanks and filters, are still in place.
- In the smelter, the initial anode baking furnace, the potline buildings, the pot shells, superstructures and busbars, are also still in place.

Preserving competitiveness has been a complex task. Since the 1970s, AOG had faced environmental challenges. On the other hand, its competitiveness had occasionally deteriorated over the years, because of energy, or market issues, or when new technological advances in the industry provided for better technical performance and product quality.

Each decade of AOG's life has been marked by some major events and challenges, that outline AOG's path to competitiveness longevity. An exception will be made, in the decade-by-decade approach, by specially referring to the period 1989-1990 that was marked by a traumatic industrial relations issue, followed by the development of a new company culture:

- The 1960s: Production capacity growth.
- The 1970s: Strategic access to Greek bauxite resources and environmental upgrade.
- The 1980s: Major Technological upgrade and production capacity creeping.
- 1989-1990: A 43-day labor strike and development of a new company culture.
- The 1990s: Further technological upgrades.
- The 2000s: Coping with ownership changes.
- The 2010s: Cost-cutting, production creeping, recycling and innovative pot control.
- The 2020s: Current energy crisis and Net Zero target by 2050.

4. Highlights of each Decade

This section will shortly highlight the major events and challenges that took place in each decade of AOG's life and the most significant investment projects, improvement actions and cost cutting projects that enabled AOG to recover and preserve its competitiveness:

4.1 The 1960s: Production Capacity Growth

- AOG's production reached its full initial capacity, of 200 kt/y of alumina and 72 kt/y of aluminium, in 1967. During the following four years, the market growth of its products and the competitiveness of AOG's plant, allowed additional brownfield investments increasing the production capacity:
  - in 1968, each existing potline was expanded from 208 pots to 260 pots,
  - in 1970, was added a new alumina production line and a new 90 kA potline of 260 pots. The pots of the new potline were simply longer than the existing ones, to contain 16 same pairs of anodes instead of 12 for the existing pots.
- Including the effect of some minor creeping projects, AOG's production reached 600 kt/y of alumina and to 150 kt/y of aluminium in 1970, more than doubling the initial capacity.
- Until the end of the decade, the technology initially used had not been challenged by new environmental requirements, or technological breakthroughs in the industry, therefore no significant technological upgrades had been necessary.

4.2 The 1970s: Strategic Access to Bauxite Resources and Environmental Upgrade

A significant investment, decided on strategic criteria, was the creation of the Delphi-Distomon mining activity. New concessions not being possible to be granted, the new activity was based on acquisitions of 3rd party bauxite mines and concessions. The operation in the existing mines was upgraded by the introduction of loaders known as LHDs (Load, Haul, Dump). New underground mines were designed for using drilling JUMBOS.

A second major investment was the collection and treatment of the electrolysis gas emissions. This became necessary in order to address a problem of dental fluorosis of sheep grazing in the surroundings of AOG's plant, due to accumulation of fluoride dust on the vegetation in dry season.

This investment project included:

- Installing two dry scrubbing gas treatment centers between the 2 potrooms of each potline.
- Hooding the pots and collecting the gas for treatment in the dry scrubbers.
- Adjusting the alumina calcination process for converting the alumina produced from floury to reactive, sandy alumina. This conversion made the alumina capable of adsorbing fluorides, when exposed to contact with the electrolysis gas in the dry scrubbers, before being fed into the pots.
- Adding closed, air-conditioned, cabins to the overhead cranes of the potrooms for protecting the operators from gas and dust emissions during alumina feeding and anode changing.
- Upgrading the pot control technology. The centralized hard-wired logic controlling the voltage control of each pot, was replaced by a central computer ensuring more reliable control, data collection and effective parameter setting.

Additionally, an industrial attempt was made on the 90 kA potline, to automatize the manual crust breaking and alumina feeding. The overhead cranes were equipped with sensors and a centralized modular hard-wired sequential logic system was developed to ensure the automatic processes. However, because of insufficient reliability, the project was abandoned and AOG started examining the point alumina feeding technology, which Pechiney had in the meantime adopted in its AP18 pot technology.

4.3 The 1980s: Major Technological Upgrade and Production Capacity Creeping

In bauxite mining, the productivity was increased by the introduction of bigger Load-Haul - Dumps (LHD), combined with automated roof bolding and mechanical scaling. At the same time, a long-term research drilling program was launched, covering all the concessions of Delphi-Distomon. It was completed many years later, after having drilled a total distance of 1 280 km.

In the alumina refinery, a major investment was the installation of a new alumina gas suspension static calciner. At the same time, several production capacity creeping projects were launched, leading to a total production capacity increase from 600 kt/y to 630 kt/y.

Some attempts of developing new technological solutions were unsuccessful:

- A chemical removal of calcium carbonate, using barium aluminate, was industrially tested but abandoned because of higher operating costs than expected,
- A new design of high-pressure pumps feeding the digestion lines, was also industrially tested and abandoned because of insufficient reliability.

For the smelter, the 1980s was a decade of major technological upgrade by converting the potlines from lateral manual alumina feeding to central automatic alumina point feeding

Adapting the new AP18 technology as such, was prohibitive for AOG because this would require shutting down the pots and replace their superstructures and anode beams, to create the space required for placing the alumina hopper and feeding equipment. AOG needed a tailor-made solution of a low-cost conversion without any loss of production. Because the Pechiney technology team had other priorities, AOG developed its own point-feeding technology and successfully applied it [1]:

- The design included one feeding point for the70 kA pots and two feeding points for the 90 kA pots. To create the required free space at each feeding point, one aluminium plate was welded at each side of the anode beam, increasing locally the width of the central channel at the feeding location.
- The feeding holes on the crust of the pot were opened, before feeding, by an air cylinder fixed on the existing superstructure and equipped with a chisel and a crust scraper. A patented device stopping the chisel descent at the detection of electrical contact with liquid bath, ensured a smooth crust breaking operation, preventing any negative consequences from the hammering effect due to the removal, by the scraper, of the crust built-up on the chisel.
- The alumina hopper, including a small aluminium fluoride compartment, was installed at the extremity of the pot, with two respective volumetric feeders filled by gravity, using input and output pneumatic valves. The doses were conveyed to the feeding points through pipes using compressed air. Only a third small hopper feeding crushed bath by gravity, was installed on the existing superstructure above the feeding point.

The development of a new pot control system was a major component of the conversion to automatic point feeding, representing around 50 % of the total investment cost. It consisted of installing a microprocessor on each pot, with associated sensors, connected to a central computer. The process control included:

- The monitoring of the potline amperage, the voltage of each pot and the electrical contact between the crust breaking chisel and the liquid bath.
- The generation of action commands to the anode beam and to the feeders of alumina, aluminium fluoride and crushed bath.
- Regulation algorithms involving the calculation of the trend of the so-called pseudo-resistance of the bath and the treatment of the electrical contact between the crust breaking chisel and the liquid bath. An additional new patented test, called ΔR, was used for automatically commanding aluminium fluoride feeding. The test consisted of periodically raising, for a limited time, the anode beam by a given distance and measuring the effect on the pseudo-resistance of the bath.

The results of the conversion project to point feeding have been extremely positive and vital for the future of AOG. The actual project payback time was only 2.8 years, due to the low investment cost and significant gains in the labor productivity, current efficiency, kWh/t consumption and cathode life duration [2].

4.4 1989-1990: A 43-day Labor Strike and Development of a New Company Culture

Before going further with investments and technological upgrades, it is important to highlight a major industrial relations evolution in the 1980s which led to a 43-day labor strike in 1989 that triggered a fundamental change in AOG's management practices.

A build-up of excessive union rights expectations, regarding co-management, cultivated since 1981 by politicians and union leaders, had made enterprise agreements more and more difficult to achieve. During this period, annual AOG enterprise agreements were systematically achieved only after labor strikes, initially of short duration. Progressively, however, the escalation of claims led to longer annual strikes, that still were kept under control of the union. Ultimately when the 1989 strike was launched, with claims impossible to satisfy, nobody knew how to stop it:

- For 43 days the AOG plant was occupied by the strikers. The basic production operations required for preventing the shutdown of the potlines, were done by safety teams under the union control.
- After using various practices used to ensure that the produced metal was not salable as such, the strikers started to verse the molten metal in a pond for waste liquids, instead of casting it in the casthouse.
- The strike ended suddenly when the strikers realized that a management decision was made to shut down one potline to avoid further damaging the installations.
- One immediate problem was the recovery of around 6 kt of metal solidified in the pond, forming a "lake" of 2 800 m2 of surface and a depth varying from 0.5 to 2.0 m. After some failed attempts of using explosives, giant circular saws and other proposed innovative ideas, the recovery was achieved in 9 months by combining the use of oxygen flame cutting at the areas of massive solidification, and the use of bulldozer's riper tooth, dragging and taking off thin layers of metal formed on top of other previously created solidified metal layers.

Figure 3. Aluminium lake.

However, AOG realized that there was a major underlying challenge regarding the company culture. There was a perception in the workforce, that the role of the front-line foremen and team leaders was limited to operating tasks. The internal communication on the factory floor, regarding company matters, was mainly driven by the union.

To prevent a new crisis in the future, AOG invested significant working time in internal communication, in clarifying the respective roles of the union and the management line and in reviewing the management practices. A home-made intense management training program on leadership was carried out over two years.

A major change in the company culture, was the introduction of a perception that:

- C.I. was part of the role of every employee.
- Every employee, supervising even the smallest team, had a role in sharing the company objectives with the team members, regularly informing them of new events and decisions,

explaining how these would affect the plant's competitiveness and encouraging everyone's involvement in C.I. processes.

Initially, the company union resisted this change but when the workforce attitudes started changing, it adopted a constructive approach. Since, it has been a management's permanent objective to maintain such an effective company culture. A continuous effort in new employee onboarding has been required, in order to cope with the ongoing workforce turnover.

At a second stage, the old concept of Quality Circles was replaced by systematic "Natural C.I. Teams" (employees following the same shift program) trained in applying C.I. basic principles and tools (teamwork, recognition of internal customers, goal setting, problem solving, action planning, costing and payback criteria, presentation for budget approval and assisted implementation). Progressively, almost the whole workforce was involved in C.I. processes.

4.5 The 1990s: Further Technological Upgrades

In parallel with the efforts to develop and maintain an adequate company culture, there was a focus on improving performance by addressing technical issues and by upgrading technology.
In bauxite mining, the productivity was further increased by (LHDs) of larger capacity combined with the use of underground mining trucks. At the end of this decade, the bauxite mining production approached 1 million t/y, while AOG's plant production capacity remained unchanged at 630 kt/y of alumina and 166 kt/y of aluminium.

In the alumina refinery:

- The hurdle of high calcium carbonate content in the Greek bauxite was finally addressed by installing a hydrometallurgical bauxite beneficiation process using a heavy media of intermediate density.
- Other technological projects aimed at improving the precipitation performance by additional processing of the Bayer sodic solution at the end of digestion through:
  - Coolers enhancing the precipitation productivity.
  - Cyclones improving the effectiveness of the grain classification at the precipitation.

In the smelter, the major investment was the installation of a centralized cleaning of the anode butts in controlled conditions, instead of cleaning each butt on the side of the pot after anode replacement. This investment completed the modernization of the smelter and was a significant improvement in terms of environmental protection and working conditions in the potlines.

4.6 The 2000s: Coping with Ownership Changes

In the 00's, Delphi-Distomon started to implement a fading out mining plan until 2030, optimizing the exploitation of its remaining reserves and the management of its resources. Production was progressively reduced from around 1 million t/y to 0.6 million t/y. At the same time, significant improvements were made regarding:

- Operating costs, through subcontracting.
- Health and safety matters by installing a sophisticated underground wireless communication system and a real time monitoring of emission elements and ventilation control.
- Environmental protection, by using already exploited bauxite lenses as backfilled voids for the access drifts waste and by smart tree planting.

In the alumina refinery, the technology upgrade projects continued, and alumina production capacity creeping projects resumed:

- Sodium aluminate filtration effectiveness was improved by the installation of new filters.
- The Bayer productivity and reliability were improved by a new process control system.
- A new "Sweetening" investment project boosted the alumina production capacity from 630 kt/y to 750 kt/y and improved the production costs. The project consisted of an additional line using imported tropical bauxite and the remaining enthalpy in the steam at the end of the existing high temperature digestion lines.

However, while approaching the mid-2000s, investment projects slowed down because AOG faced a major threat. Alcan had acquired Pechiney in 2003 and, after investigation, AOG was assessed as an asset not compatible with Alcan's standards in terms of electricity supply. The AOG's 40-year electricity supply contract with PPC was to end in March 2006 and there was no perspective of signing a new contract at a price acceptable by Alcan. AOG was put on sale. In case of failure, AOG's survival would be at risk.

All expected potential buyers declined to make any final offer. Fortunately, Mytilineos SA, a family company active in metal trading, manufacturing and construction, decided to also become a primary aluminium producer and finally acquired AOG in 2005.

Under Mytilineos ownership, PPC continued to supply electricity to AOG after the expiration of the initial contract, in terms that required hard negotiations. At the same time, Mytilineos launched the construction of a 334 MW "High-Efficiency CHP" (Cogeneration Heat & Power Plant) using natural gas, capable of delivering 200 MW thermal power capacity to the alumina refinery and having an overall efficiency (electrical + thermal) > 75 %.

The new CHP was built by the Mytilineos' SES BU and has been operated by the Power and Gas BU. As it covered the alumina refinery needs for high-pressure steam, the existing steam generating unit, using heavy fuel oil, was stopped. The electricity produced by the CHP was sold to the Greek wholesale market at a feed-in tariff justified by a fuel saving of >10%, as compared to separate generation of electrical and thermal energy.

The replacement of heavy fuel oil by natural gas was extended, as a matter of policy for reducing the CO_2 footprint, to other installations.

The next impressive Mytilineos' initiative was a commercial breakthrough of directly importing Liquefied Natural Gas (LNG). Until then DEPA, the state-owned gas facility, was a monopole importing natural gas for the whole Greek market. The first Mytilineos' LNG shipment failed to reach the DEPA-owned LNG terminal because of undue bureaucracy but, since, the actions taken by Mytilineos have ensured smooth systematic imports.

Under Mytilineos ownership, AOG's investments, aiming at production capacity increases, production costs savings and technological upgrades, resumed:

- The alumina production capacity reached 795 kt/y at the end of the 2000s following a capacity debottlenecking project at the precipitation stage and at some other stages of the Bayer process.
- In the casthouse, a step change was achieved in the quality and the mix of products by investing in billet hot top casting technology, in increasing the maximum billet length and the billet production capacity and in product quality control equipment (Liquid Metal Cleanliness Analyser (Limca CM) - Porous Disc Filtration Apparatus (Podfa) Analyzers, ultrasound scanner for billets, Ceramic Foam filters, Chlorine free degasser).
- At the same time, the bauxite residue press filtration testing was completed and Mytilineos approved the industrial investment project which enabled AOG to stop disposing the red mud into the sea. Since, the bauxite residue produced has been filter-

pressed at moisture levels <28 % and stored in controlled conditions, with parallel rehabilitation. The actual storage capacity is sufficient for 20 more years.

- Bauxite residue (BR) recycling has been tested in various industries such as cement, steel, brick/tile and in landfilling. Since, more than 330 kt of BR have been recycled, while AOG has been demonstrating a very active participation in relevant recycling European R&D projects.

Before the end of this decade, AOG faced another major challenge. As a result of the 2008 worldwide economic crisis, the aluminium prices fell by more than 50 %, in the first half of 2009, as compared to the first half of 2008. AOG's operations were losing money at a daily rate of around US$ 0.5 million. However, AOG survived the market crisis because of a risk-hedging done timely by Mytilineos before the start of the economic crisis, against the analysts' predictions that aluminium prices would further increase.

4.7 The 2010s: Cost-Cutting, Production Creeping, Recycling and Innovative Pot Control

AOG survived the market crisis but realized that its position had deteriorated on the worldwide alumina and primary aluminium cost curves. A number of non-competitive alumina refineries and smelters had shut down, while others had made significant efforts to improve their production costs.

AOG reacted with determination by launching 4 successive cost cutting projects with cumulative recurring savings exceeding US$ 100 million/y, that brought AOG to the 1st quartile of the world alumina and aluminium production cost histogram:

- "THE FUTURE" over 2012-2014.
- "EXCELLENCE" over 2015-2016.
- "THE BEST" over 2017-2018.
- "HEPHAESTUS" over 2019-2020.

Every cost item was reviewed and adjusted, including challenging electricity and gas supply terms, raw materials procurement terms and freights, product sale prices and subcontracting terms. Significant labor cost cuttings were agreed with the company union.

Figure 4. Impact of cost cutting projects.

Home-made training programs on management change were carried out, while the C.I. teams, with participation of almost all the workforce, contributed systematically in cost cutting with smart high return project proposals, or with savings without any capital expenditure. A typical example of such smart projects, was the conversion of a fuel oil tank, unused since the CHP startup, to caustic soda tank providing for optimized caustic soda procurement and trading.

As part of the competitiveness improvement program, the production capacity was increased through debottlenecking, or creeping, or equipment upgrading investment projects in both the alumina refinery and the smelter:

- In the alumina refinery:
    - The production capacity increased from 795 kt/y to 865 kt/y. This was achieved, on the one hand, by additions of new equipment in digestion, precipitation and recovery of solid hydrate alumina in spent liquor and, on the other hand, by equipment and process upgrades that improved efficiencies in the areas of bauxite grinding and digestion.
    - Additionally, operating costs savings were achieved by installing a second alumina gas suspension static calciner, by improving the productivity of the bauxite residue press filtration and the Greek bauxite beneficiation process and by recovering the heat of condensate recycled in the cogeneration unit.
- In the potlines:
    - The primary aluminium production creeped from 166 kt/y to 185 kt/y through amperage increase resulting from enlarged anodes and more conductive side blocks in the lining of the pots.
    - Tests of modified cathode designs, aiming at reducing the specific energy consumption, have been launched on a number of pots.
    - Pot power modulation was tested but was put on hold because AOG's request to the Greek Regulatory Authority for Energy, to establish a scheme rewarding such a service by the power transmission operator, was unsuccessful.
    - Production of high-purity aluminium (>99.9%) in selected pots was also tested but was abandoned because the premium was insufficient to cover the extra cost.
- In the casthouse, the production cost and the quality and mix of products were improved through investments:
    - Converting the furnaces from heavy fuel oil to gas and revamping the furnace dumpers.
    - Upgrading the billet homogenizing process through a new software and developing, with the University of Volos, high extrusion speed billets 6000.
    - Increasing the maximum slab length, the slab production capacity and installing a new Wagstaff casting line for slabs.
    - Installing a Robotized Spectro Analyzer and a new Rotary Flux Injector (RFI), Alkali and Inclusion Removal Technology.

Three additional special investment projects are worth attention:

- A strategic investment project in aluminium recycling, named "New ERA 250", including the introduction of a 15 kt/y remelting activity in the casthouse, the acquisition of EPALME, a 37 kt/y secondary aluminium facility and the increase of EPALME's production to 50kt/y. With this investment, AOG's total aluminium production capacity reached 250 kt/y.
- A smart investment project rehabilitating the 55 years old anode baking furnace [3]: A 90-day major repair took place in the anode baking furnace, an open top ring type furnace erected in 1966. This was a typical example of AOG's smart project approach, aiming at increasing the lifespan of an existing equipment at a reduced cost, as compared to a full

reconstruction. The result was a successful reconstruction of the heavily stressed central casing elements with a minimum impact on the refractories.

- An innovative digitalization project, named "The Digital Smelter" was launched in collaboration with GE [4] to enhance AOG's smelting process control and performance. An adaptive real time virtual replica of each pot has been developed, combining the pot historical data with physical, thermal and electrical modelling of the Hall-Heroult process. Each individual virtual pot replica provides real-time information on the health of the real pot, as well as predictions, advanced alerts and recommendations, on treating issues of the specific pot.
  This project is the first stage of AOG's plan to be part of the 4th Industrial Revolution (Industry 4.0) by digitalizing the processes of both the alumina refinery and the smelter.

4.8 The 2020s: Current Energy Crisis and Net Zero Target by 2050

For the near future, the first priority is to cope with the extraordinary challenges set by the current energy crisis threatening the European industries at the company level, taking into account the diversified activities of Mytilineos BUs.

At the same time AOG has set a Net Zero Target by 2050, as part of the Mytilineos' global target.

- Starting from 2023, AOG will progressively move from a 100 % electricity supply from PPC, to a mix which will contain increasing part of green electricity, leading to 100 % green electricity by 2050.
- At the same time, AOG will increase its recycling capacity, while investing in existing, or new, technologies reducing its carbon footprint and its energy consumption.

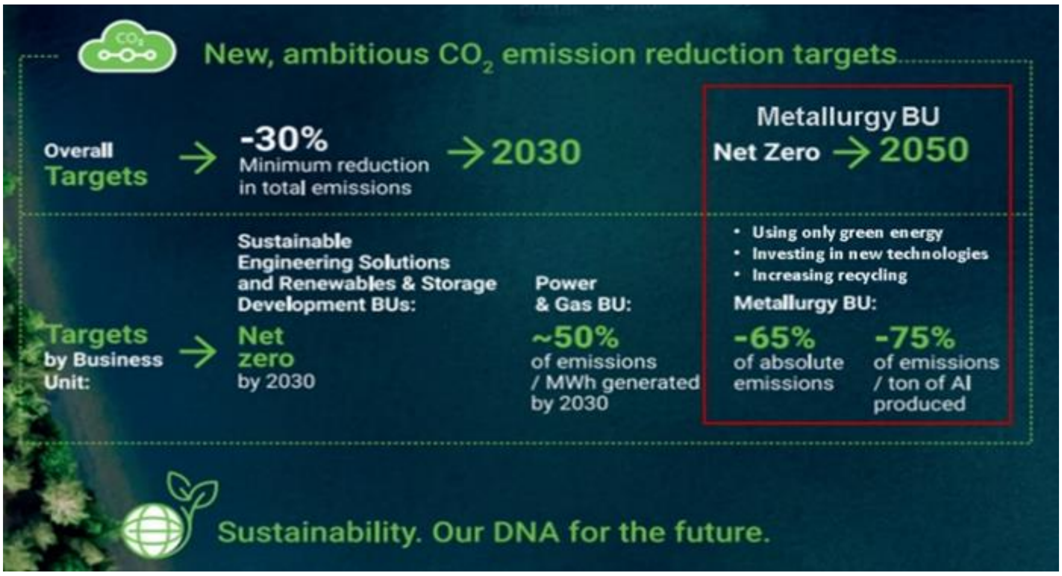

Figure 5. AOG's Net Zero Target by 2050, as part of the Mytilineos global target.

5. AOG's Human Resources – a Crucial Longevity Key Factor

So far, we have described how AOG provided for its competitiveness through successive smart investment projects over the decades, limiting the purely defensive investments to the minimum necessary. Typical examples of major successful smart projects were the home-made conversion of the pots from manual alumina feeding to automatic point feeding at a minimum investment cost and the repair of the 55 years old anode baking furnace instead of a full replacement. The technological awareness of the management team and the technical capability of the organization to find original solutions and apply them, have been crucial in designing, getting shareholders' approval and successfully implementing such investment projects.

We have also referred to a large number of C.I. successful actions requiring small, or no investment costs.

- As part of Pechiney until 2003, AOG had excelled in developing a good understanding of the C.I. concept, tools and processes, by the whole workforce. The C.I. activity was enhanced by the significant internal communication and training effort done after the traumatic labor strike in 1989. The participation in C.I. teams was boosted by the developed cultural perception that C.I. was part of the role of every employee and that employees supervising others, had a communication role of keeping their teams aware of the company events and objectives.
- As part of Alcan, AOG enlarged the C.I. activity. While the widely spread Natural C.I. Teams continued to perform, specialized Project Teams, led by qualified Six Sigma Green Belts, or Black Belts, started to address more complex problems, using more sophisticated C.I. tools.
- As part of Mytilineos since 2005, AOG pursued C.I. activities and used the know-how and skills developed in the other BUs of the company. The company culture promoting C.I. was maintained through a series of training programs developed and carried out by the line management, in the areas of safety, communication, leadership, change management, specific professional skills and C.I. methods and tools.
- In the preceding sections, significant C.I. results have been mentioned in the list of improvements made in each decade. However, a complementary standpoint to better perceive the full C.I. picture, is looking at the list of successful C.I. projects implemented in various AOG departments. As an example in the casthouse, the list of C.I. projects includes: "New water flow control", "New starting head and molds", "New filer bags", "New metal level controls", "New continuous lubrication" and so on. Such a list shows that improvement projects have systematically been launched on each equipment and each working practice, at every step of the operations.

Another AOG's activity, relying on specific competencies and motivation of human resources, has been Research & Development, particularly regarding sustainable development. AOG has been participating in 23 European Projects including bauxite residue valorization, recovery of Gallium and Vanadium (Ga/V), Spent Potlinings (SPL) Valorization, waste heat to power / renewable energy and aluminium recycling. More than this, AOG has installed Pyro- Metallurgy and Hydro-Metallurgy Pilot Units supported by dedicated Infrastructure [5], [6].

Finally, a recent innovative development, shows the importance given by AOG to the human quality of life even outside the plant, in Aspra Spitia the "home city" of employees. This development is the Smart City project, the first project of the new MYTILINEOS "Smart Cities Services. A "smart" city is technologically upgraded with digital innovations aiming at improving quality of life, enhancing citizens' active involvement.

The smart free services include:

- Flexible energy management services and smart water and waste management.
- High operability in public areas (appliances charging spots, internet 4G/WI-FI access, sound systems for citizens' direct communication with public services, weather forecast information, access to lighting options).
- Continuous education on issues of energy, water and the importance of technology. raising the citizens' awareness of environmental and energy issues and the Net Zero objective.

- Central control systems providing direct information with a view to promptly resolving issues through remote management.

The initial smart structures and facilities are planned to be constantly upgraded, interacting with citizens, while at the same time the use of resources will be optimized and the direct and indirect emissions will be reduced.

6. Conclusions

Greenfield aluminium smelter projects require a huge construction investment capital implying a long project payback period. During this time, the initial situation often changes dramatically, affecting the viability of the smelter. AOG is an interesting case study because, despite the dramatic changes in the aluminum industry over the last 5 decades, it has preserved its competitiveness maintaining an excellent state of its equipment and its operational performance.

AOG's production capacity, initially 200 kt/y of alumina and 72 kt/y of primary aluminium in 1967, is today 0.6 million t/y of bauxite, 865 kt/y of alumina and 250 kt/y of aluminium (185 kt/y of primary aluminium, 15 kt/y of recycled post-production scrap and 50 kt/y of secondary aluminium).

Preserving competitiveness has been a complex task. In every decade, AOG faced and effectively addressed various types of challenges, environmental, technological, industrial relations, changes of ownership, aluminium market crisis, energy crisis, etc.

AOG reviewed its management practices after a traumatic 43-day labor strike in 1989 and developed a new company culture including the perception that C.I. is part of the role of every employee. Since, this company culture has been systematically maintained.

Overall, more than 600 million Euros of capital have been invested over the decades, in projects upgrading technology, improving production costs, products' quality, safety and working conditions and ensuring compliance with environmental toughening regulations. The successive AOG's shareholders felt comfortable in approving such investment projects because:

- AOG's management and technical experts had developed the capability of elaborating home-made solutions and implementing "smart investment projects" to successfully address challenges at a minimum cost.
- A very large number of C.I. successful projects, involving almost all the employees, had demonstrated that many problems were solved without requiring significant capital cost.
- When it became necessary in the 10s, AOG demonstrated its capability to successfully implement 4 successive cost cutting projects with cumulative recurring savings exceeding US$ 100 million/y, including reduction of labor costs.

AOG is committed to sustainable development through R&D and innovation. So far, it has been participating in 23 EU R&D programs and has installed relevant pilot plants, while two innovative projects are underway, the "Digital Smelter" and the "Aspra Spitia Smart City".

Today, AOG is ready to face with determination the current challenges of the European aluminium industry and the Net Zero Target by 2050. It will be shifting progressively to an electricity mix which will contain increasing part of green energy, up to 100% by 2050, it will increase its recycling capacity and it will elaborate and implement smart investments in existing, or new technologies, reducing its carbon footprint and its energy consumption.

AOG's story and its today's situation and performance, demonstrate that competitiveness longevity can be achieved by sustainably combining investment capability, managerial technical awareness and skills and a shared company culture promoting C.I. as part of every employee's job.

AOG's story also shows that in extraordinary circumstances threatening the survival of a smelter, courageous business decisions implying costs and risks may be required to provide opportunities for addressing the issues. Again, such business decisions rely on the confidence of the shareholders that the smelter will not only survive the crisis, but will also do what is needed to ensure its competitiveness.

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