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Abstract

Worldwide, the manufacturing industry is now aiming for competitive advantage and increased profits. To remain competitive, a manufacturing company needs to use tools that provide it with a distinctive competitive edge. This research first discusses the manufacturing process of aluminum, the world and the Indian aluminum industry, technological changes in the aluminum industry. In the second part we discuss a literature survey of various operation research models in the aluminum industry. The survey has been done through the published research works from 1967 till the present year. The purpose of this study is to survey models which are related to the aluminum industry either in methodology or in practice. The study lists the opportunities for OR/MS in the aluminum industry and the major challenging areas for research. It also motivates researchers to explore more such problems in operations research and management science related to aluminum manufacturing.

1. Introduction

Aluminium is the third most abundant element in nature – comprising some eight percent of the earth's crust. Today more aluminium is produced each year than all other non-ferrous metals combined. Aluminum is light, strong, conductive, durable, flexible and easy to recycle. Among a wide diversity of applications from art and crafts to high technology, the three main fields in which aluminum is used are transportation, packaging and building and electrical amd macine tools. While discussing the aluminum industry the first point that comes to our mind is the production and the shipment of aluminum.

The total production and the sales of aluminum in the USA, which include domestic (building, transportation, consumer durables, electrical, machinery, containers, other) and exports account to 22.150 million of pounds in North America. Based on this, the percentage of apparent consumption by market in North American Aluminum industry as per 2008 year is as follows (see Figure 1):

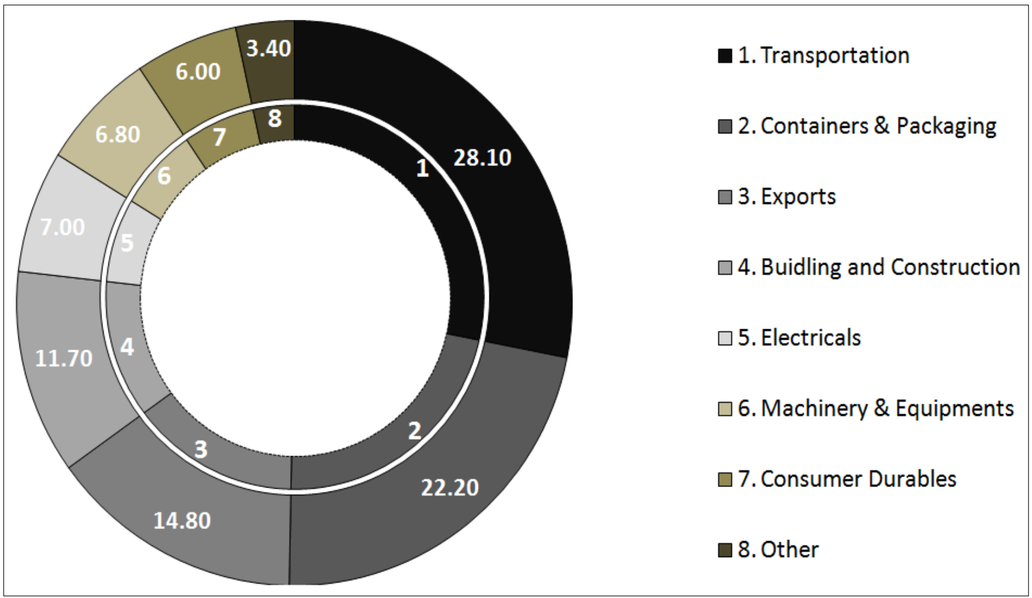

Figure 1: Percentage distribution of aluminum shipments in major U.S. markets (based on 2008 information)

Source*: Industry Statistics, the Aluminum Association, 2012*

In the later part of the paper we discuss that the world aluminum industry is about 88 billion dollars industry and we need aluminum in a large number of our consumptions. As Operations Research and Management Sciences are tools to improve efficiency of manufacturing systems, it is expected that greater application of these tools, more is the chances of cost saving and profit improvement in the industry. Hence recognizing that aluminum industry is important mineral process industry we believe that applications of OR/MS has the potential to become a distinctive competence for an aluminum company. Hence there is need to survey the application of OR/MS in the process industry.

1.1 Organization of the Paper

In the second section, we discuss the manufacturing process of aluminum. In the third section we concentrate on the world aluminum industry followed by the description of the Indian aluminium industry in the fourth section.. Since the net sales from India is more than 10 billion USD, and India is the seventh largest Aluminum Oxide Production, we discuss some specific issues related to India In the fifth section, we explain the technological changes in the aluminum industry. After this, section six looks at the possible future changes in technology in the industry. Finally, we discuss the applications of OR/MS in the aluminum industry.

Our survey is two kinds of audiences. First, the the aluminum industry which is always on the look out for recent OR/MS advances which can be implemented, and second, academicians and researchers interested in conducting research in the discipline of mathematical modeling in general and the aluminum industry in particular.

We explore the possible areas of research in the aluminum industry using OR/MS techniques through a detailed study of the manufacturing process right from the mining stage to the end product. We then look at the areas in which research has been carried out for the aluminum industry using OR/MS models. Technology improvements in manufacturing are also discussed to understand their impact on possible areas of research. However, we have not studied the research on environmental issues and pollution control in the industry.

2. Manufacturing Process of Aluminum

Aluminum is produced in three stages as follows:

1. ***Mining***: In first stage the bauxite ore is mined and cleaned.

2. ***Refining***: In the second stage,alumina is refined from the ore using Bayer's process (explained in sub section 2.1).

3. ***Smelting***: The last and final stage in aluminum production is smelting the alumina into aluminum (described in sub section 2.2).

A brief description of the aluminum production process is given below.

2.1. Bayer's Process for Alumina Production

Bauxite is the principle ore of aluminum. The composition of bauxite is alumina (40-60%), silica (silicon oxide), iron oxide, and titanium dioxide. Bauxite is transformed into rich alumina (aluminum oxide) powder through Bayer's process.

In the Bayer process, Aluminum Oxide Al_2O_3 is dissolved in hot sodium hydroxide (NaOH)solution in the digester and the iron oxide and other oxides are removed as insoluble "red mud."

$$Al_2O_3 + 3H_2O + 2NaOH + heat \rightarrow 2\ NaAl(OH)_4 \quad \text{...(1)}$$

Aluminum hydroxide, $Al(OH)_3$ is precipitated from the clarified solution by cooling and seeding. The washed precipitate is calcined at 1200°C to produce anhydrous alumina.

$$2Al(OH)_3 + heat \rightarrow Al_2O_3 + 3H_2O \quad \text{...(2)}$$

The particle size of the alumina is about 100 µm (µm = million^th^ of a meter) and is called "ore" in the electrolytic reduction plants. Alumina is then further reduced to liquid aluminum metal via an electrolysis process (also known as the Hall-Héroult process).

$$2Al_2O_3 + 3C \rightarrow 4\ Al + 3\ CO_2 \quad \text{...(3)}$$

2.2. Hall-Heroult Process for Aluminum Smelting

Aluminum is available in the form of Bauxite in the earth's crust. The main raw materials for the manufacture of aluminum include Bauxite, Caustic soda, Calcined petroleum coke, coal tar pitch, and furnace oil. The production of aluminum from bauxite involves three phases. The conversion ratio of alumina to aluminum metal in the Hall Heroult process is 0.5.

The Hall Heroult process takes place in reduction cells or pots, which are steel boxes of various sizes lined with carbon. The alumina is dissolved in a molten salt called cryolite. Aluminium fluoride is added continuously to the molten electrolyte to maintain the required density, conductibility, and viscosity. A carbon electrode (the anode) is lowered into the solution which causes a continuous electric current to pass through the mixture to the carbon pot lining, which acts as the cathode. After the solution gets electrolysed at 970 degree Celsius, the dissolved alumina separates into aluminium metal and oxygen. The aluminium is heavier so it is attracted by the cathode to the bottom of the pot while the oxygen settles on the carbon anode to form carbon dioxide. Thirteen to fifteen thousand kWh of electricity is used to produce one ton of aluminium. The anode is consumed during the operation.

The molten aluminium in the pot is siphoned into crucibles and transferred to alloying furnaces. In the casting/ingot area, the molten aluminum is casted at a temperature of over 700 degree Celsius to form ingots, T-bars or long cylindrical logs, large blocks called extrusion billets. The metal can be then cast as pure aluminum (better than 99.7%) or small amounts of other elements, such as magnesium, silicon, manganese, iron, zinc or copper are added to form aluminum alloys. During this process, the Continuous casting of molten aluminium is also done to get the required metallurgical property.
The aluminum formed during this process is known as primary aluminum. Aluminum can be easily and economically recycled by melting and casting into products without losing any of its properties. Recycled aluminum is known as secondary aluminum. Recycling aluminum uses 5% of the energy needed to produce the primary metal from bauxite. The flow chart below summarizes the whole mechanism of aluminum production (see Figure 2):

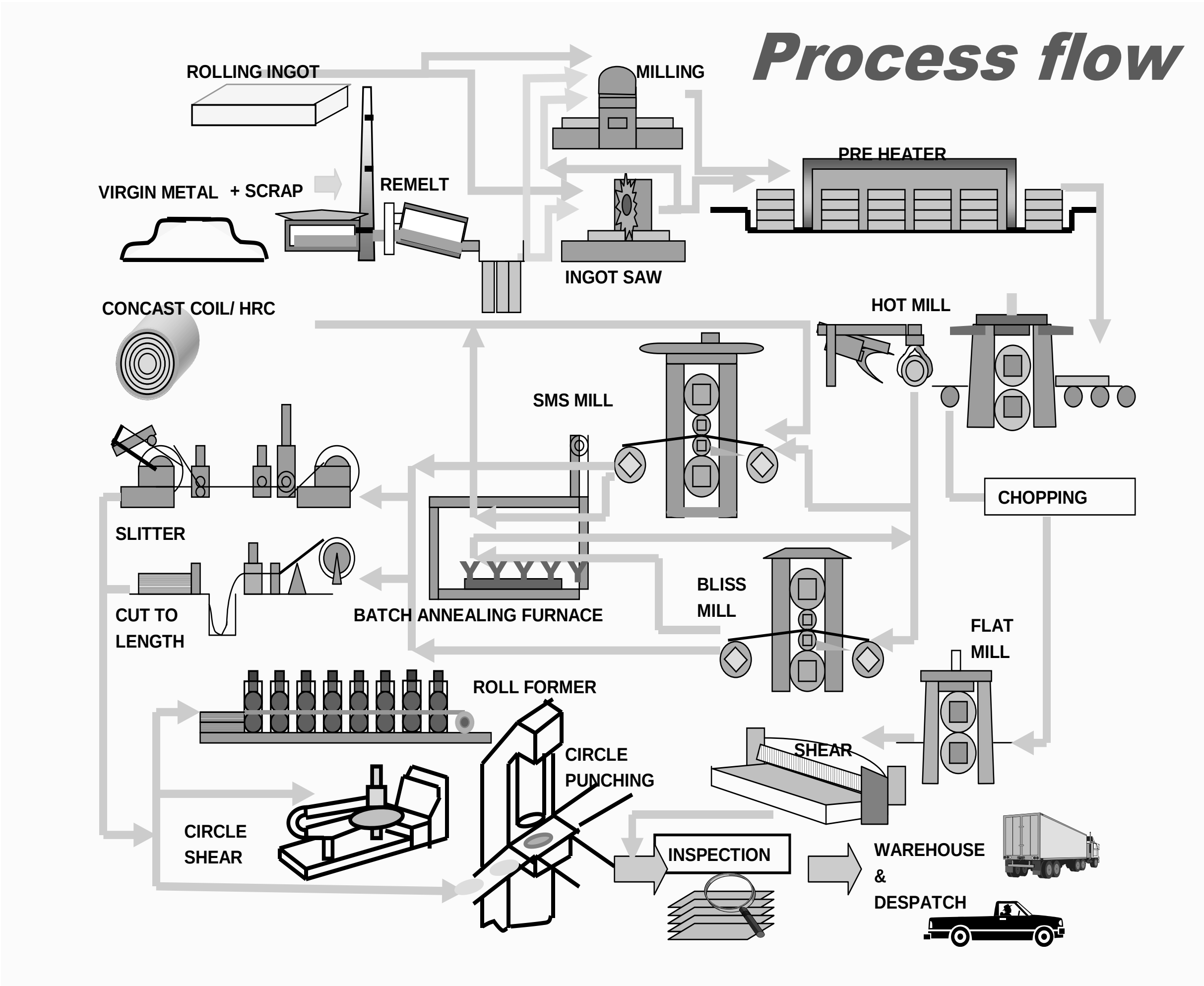

Figure 2 : Aluminum production process

2.3 Research on Alternative Aluminum Production Processes

Over the years, the industry has looked at alternative methods of extracting aluminium because of the high energy and other costs associated with the Hall-Heroult process. Research has explored the carbo-thermal process which requires temperatures greater than 2000 degrees Celsius for direct reduction to take place, and alternatively a process which involves electrolysis of anhydrous aluminium chloride.

There is a list of various other processes which can be used as an alternative in future for extraction of aluminium. These processes have been shown to produce aluminium, but for a variety of technical reasons they have not been translated into viable commercial scale plants. A lot of research is being done to fully develop these processes so that aluminum can be produced in a sustainable way. At the same time considerable research effort has been made by the metallurgists in the research laboratories in the industry as well as in the academia, to improve the efficiency of the Hall Heroult process (see Table 1).

Alternative Processes	Advantages Over Hall Heroult	Disadvantages Over Hall Heroult
1. Alcan process	Substantial capital and operational benefits	Aggressive stress corrosion associated with handling of gaseous $AlCl_3$
2. Alcoa process	Higher conductivity of electrolyte (4sm/cm vs 2.3-3sm/cm in Hall Heroult) Lower energy consumption Higher efficiency	Problem related to chlorine handling, corrosion , environment issues
3. Carbon reduction process	In the research and development phase, this production process is a new technology and holds the potential to produce aluminum at a lower cost, with lower energy requirements, and lower emissions at a lower capital cost	High temperature leading to more electricity consumption
4. Reynolds process	Low capital cost	Problem with construction of furnace and material stability at operational conditions
5. Toth process	Several types of ores with Al_2O_3 content as low as 30-40% can be used as raw material for aluminum production	Low aluminum yield, higher cost,

Table 1: Depicting alternative routes of aluminum production

A review of the different aluminum production processes shows that there are attempts by researchers to develop a new technology to produce aluminum. The attempts relate to the use of the right materials for the key reactions or electrodes, reactor designs which can have a higher rate of productivity per unit volume than existing technology, heat balancing, etc.

3. World Aluminum Industry

The aluminium industry now is very different from what it was forty years ago. More than 40% of the world's bauxite production is accounted for by BRIC economies (Brazil, Russia, India, China) while the alumina output has shifted towards bauxite-rich countries (Guinea, Australia, Vietnam, Brazil, India) and away from industrialized economies. Due to the continuous increase in energy prices and in some cases due to government industrial policies, primary production has moved from regions such as the United States, Japan and most West European countries towards China, Russia, Canada, Brazil, Australia, the Middle-East, and now India and some parts of South East Asia. The world's major producer of aluminum in 2012 was China (45% of the total). The Commonwealth of Independent States (CIS) (10%), Europe (9%) and North America (10%) traditionally remain important production areas. Regions such as the Middle East and India are emerging as important producers of primary aluminum (see Figure 3).

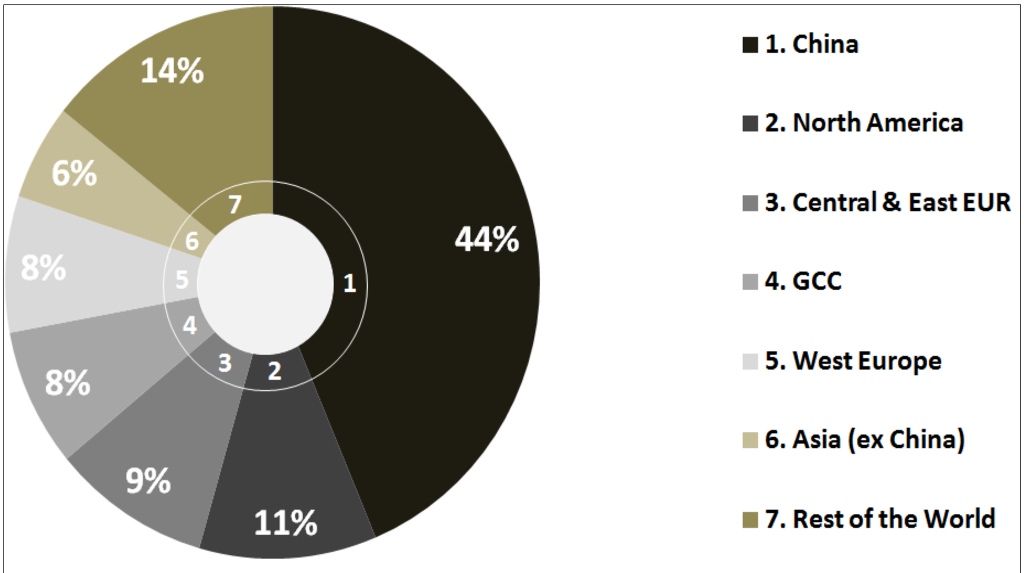

Figure 3: Primary aluminum producing regions in 2012 ('000MT)

Source: *European Aluminum Associationhttp://www.european-aluminium.eu/about-aluminium/facts-and-figures/ retrieved on May 31, 2013*

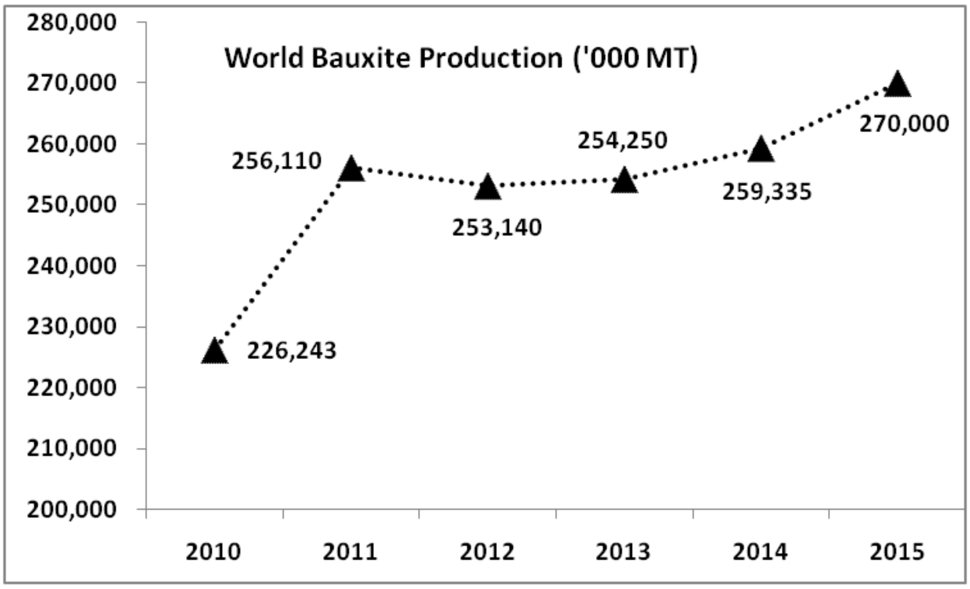

Figure 4: World bauxite production over years (‘000 metric tons)

Figure 4 shows the world forecast for bauxite production for 2015.

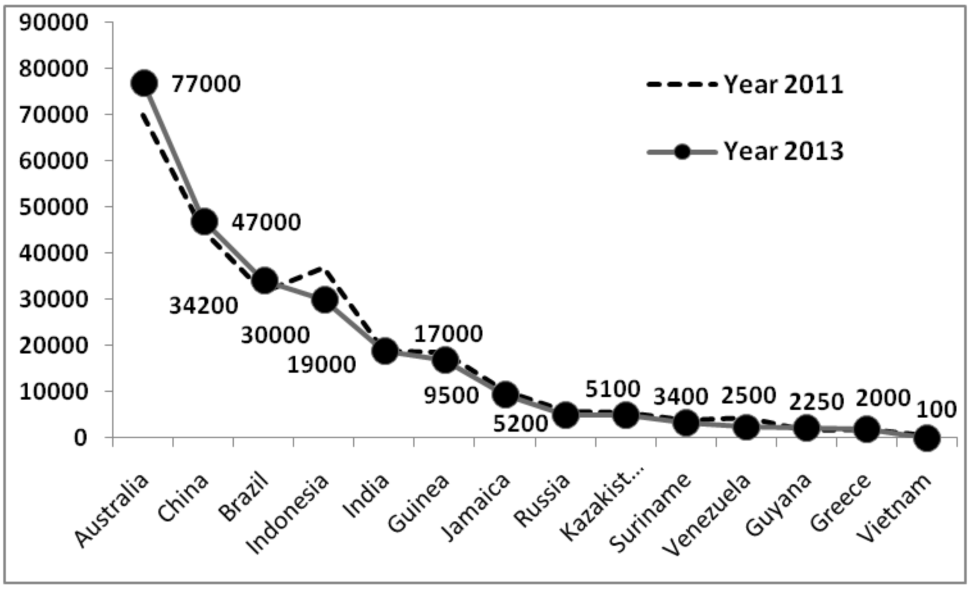

Figure 5: Country wise world bauxite production (‘000 metric tons)

In Figure 5, we plot the bauxite production from different countries for 2011 and 2013. While we had access to the data of the past few years, the plot of the two alternate years indicates that the world bauxite production pattern has not changed. Australia remains the largest producer of bauxite followed by China, Brazil, Indonesia and India.

The table in Appendix B shows a detailed analysis of world's aluminum production from 2000-2012. From the table, we can see that world aluminum production has risen from 24.65 million tons in 2001 to 45.27 million tons in 2012. Till 2000, North America was the largest primary aluminum producing country in the world with a capacity of 6.072 million tons, In 2011, China produced 17.78 million tons of capacity of bauxite mines worldwide is expected to increase to 270 million metric tons (Mt) by 2015 from primary aluminum making it the world's largest aluminum producing country and by 2012 China's production is 19.75 million tons.

According to the OECD global forum on environment the capacity of bauxite mines worldwide is expected to increase to 270 million metric tons (Mt) by 2015 from 183 Mt in 2006. Future aluminum production capacity is expected to reach 61 Mt in 2015 compared to 45.3 Mt in 2006, which is an increase of 35%.

By 2025, aluminum consumption is likely to increase more than 2.5 times to 120 Mt which represents a growth rate of 4.1% per year. Russia, Brazil, and India also are expected to increase their aluminum consumption significantly. Consumption in high income countries is not expected to change significantly on a per-capita basis, but due to the change in production and consumption in other countries, total consumption may change.

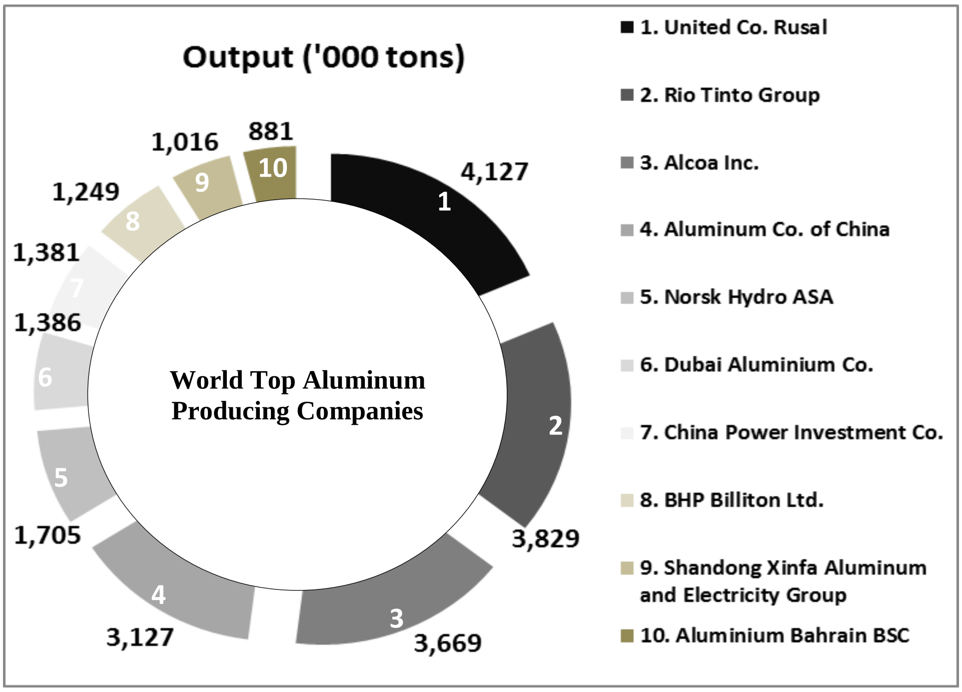

Figure 6: Top aluminum producing companies of world

Source: *http://www.bloomberg.com/ Retrieved on May 12, 2013.*

These top companies produced almost 50.85% of the world production in 2011which was 43.989 Mt of aluminum (see Figure 6).

4. The Indian Aluminum Industry

The requirement of aluminum in India is around 1.29 million tons per annum as compared to the global requirement of around 7.4 million tons. With Indian economy growing at 5-6%, the demand for aluminum has increased manifold. This demand is expected to grow by 8-10%. India is expected to have an installed aluminum capacity of 1.7 to 2 million tons per annum by 2020.

India stands fifth in terms of world bauxite reserves with a total of 2300 million tons of bauxite reserves. There are three major players in aluminum production in India as mentioned in the table below.

4.1Upstream

Upstream industries are those industries which concentrate on bauxite mining and conversion to aluminum.

Name of the Company	2009-10	2010-11	2011-12(Mar-Dec)
NALCO	0.431	0.443	0.309
HINDALCO	0.555	0.543	0.431
VEDANTA GROUP	0.537	0.642	0.498
Total	**1.524**	**1.629**	**1.239**

Table 2: Production of aluminium by primary Indian companies (million tonnes)

Source: *Compiled on the basis of information provided by the primary aluminium producers to the Ministry. (www.mines.nic.in) Retrieved on May 12, 2013.*

Most alumina refineries are located close to bauxite ore reserves to reduce transportation costs. Indian companies have a competitive advantage in aluminum production because of the ample availability of resources, low labor costs and captive power plants.

The National Aluminium Company Limited (NALCO) has improved performance in production and sales in the year 2012-13 (see Table 2). During the year, the company achieved highest-ever bauxite production of 5.42million tonnes, as compared to 5million tonnes achieved in 2011-12. Due to the increasing production the net sales turnover went up from Rs 650 billion in 2011 to Rs 681 billion, thereby marking a 4.75% increment.The company achieved a net profit of Rs.60 billion during 2012 as compared to Rs.85 billion in 2011, due to reduced Aluminium prices in London Metal Exchange and high input costs (see Table 3).

NALCO Company Parameters	2011-12	2012-13
Bauxite Production (million tonnes)	5.00	5.42
Alumina Hydrate Production (million tonnes)	1.7	1.8
Alumina Hydrate Sales (million tonnes)	0.84	1.00
Metal Production (million tonnes)	0.41	0.40
Aluminum Export (million tonnes)	0.10	0.14
Net Annual Sales Turnover (Rs billion)	650	681
Aluminum Price (USD per tonnes) in London Metal Exchange (LME)	2,317	1,976
Net Profit (Rs billion)	85	60

Table 3: Performance in year 2012-13 over 2011-12

Similarly, NALCO's Alumina Refinery has produced 1.8 million tonnes of alumina hydrate, against 1.7million tonnes achieved in 2011-12.However, during the year, the metal production of the company was reduced marginally from 0.41 million tonnes to 0.4 million tonnes, due to planned shutdown of pot shells of the smelter.In terms of sales, during the year, the company sold 1 million tonnes of alumina hydrate, against 0.84 million tonnes in 2011-12. Aluminium export by the company also increased to 0.14 million tonnes this year from 0.1million tonnes achieved in the last financial year. *The aluminium prices in Indian market are driven by the major players, and remain in alignment with the LME indexes. According to the LME the average price of aluminium in 2011-12 was $2,317 per tonnes as compared to $1,976 in 2012-13.*

Scenario portrayed in Table 3 clearly describes that all production parameters grown in year 2012-13 in comparison to year 2011-12, but the net annual profit shown substantial decrease. The decrease was primarily due to the price fluctuation at LME. The application of mathematical modelling and optimization for better resources utilization can hedge the risk of price volatility in global market.

4.2. Downstream

These are the industries which buy aluminum and convert it into recognizable customer products. The key consuming industries in the domestic market are electrical, transportation, construction and consumer durables. All three major global integrated aluminum companies, Alcoa, Rio Tinto, Alcan and Hydro, have announced significant restructuring of their downstream portfolios. Hindalco emerged as a dominant downstream player after Indal's acquisition. Its combined production capacity is over 0.15 million tons in rolled products and around 11,000 tons in foils. Sterlite's acquisition of Balco is likely to offer it 40,000 tons of rolled capacity. Nalco's acquisition of International Products is expected to provide it access to 50,000 tons of rolled products. However the two important factors affecting downstream industries are import tariff structure and demand outlook.

5. Technological Changes

The competition from alternative materials for the substitution of aluminum in consumer goods and industrial components has increased manifold. This has forced the industry to intensify its efforts to reduce the cost of production and supply chain either through improvements in the existing process by implementing operation research models or through development of alternative technologies. Several technological advances have been evolved in the production of aluminum in the last decade. While past technology improvements have greatly increased the current efficiency of aluminum cells to 96%, the industry continues to pursue research to increase energy efficiency, improve productivity and reduce emissions in primary aluminum production. The recent technological changes in smelter technology, cathode lining, anode plant and cathode design improvements have led to the improvement of operational performance, power efficiency, productivity and best dust control practices.

Several technological advances have been made in the treatment of the ore as well as the operation of the electrolytic cells.

6. Survey of OR/MS Models

In the first six sections, we discussed the aluminum industry, the various manufacturing processes of aluminum, the world scenario, and an overview of Indian aluminum manufacturing companies. With 24 million tonnes of annual production and 89 billion US dollar revenue, it is important to study the potential for improvement through OR/MS modeling. With the size of revenue generated by the aluminum industry, a marginal improvement with the application of OR/MS models can be significant in absolute terms.

We now discuss our survey of various OR/MS models applicable to the aluminum industry (see Table in Appendix A). This study covers most of the papers published in International Abstracts in Operational Research (IAOR), academic research publication databases and other internet sources. It may be worthwhile for readers to refer to another similar survey paper on integrated steel plants (Dutta and Fourer, 2001). This study does not include any kind of industrial survey. These models have been classified on the basis of various OR/MS techniques and processes used in the aluminum industry.

6.1 Models based on Optimization Techniques

Blending

This is similar to a typical diet problem or burden optimization problem in a blast furnace. In the smelting process of aluminum, there are several raw materials with different compositions of elements. The final composition of the output product from the smelter has a desired range composition of different elements. A typical blending problem is to determine the mix of input raw materials (to the smelter) that minimizes the cost of raw materials and satisfies the composition constraints of the output product.

The first reported work in this area was a linear programming model by Mel'Nikov and Babin (1967) that was used to address the problem of calculating the furnace charge in the smelting process of aluminum alloy. The problem was solved by using a linear programming model that provided an optimal plan, and a guaranteed chemical composition was obtained. A recent publication reported by Chen and Yang (2009) reported a mixed integer programming model. The model was based on logistics planning and OR/MS. The optimization model was developed for site selection and rational ore blending. They demonstrated a feasible and implementable solution, but no actual implementation has been reported.

Cutting Stock Optimization (CSP)

Stadtler (1990) reported the results of one dimensional CSP. The paper presented a new code which is supplemented by a one pass branching procedure. Such a heuristic solves the problem of estimating the number of aluminum profiles according to customer specification.

Helmberg (1995) described an LP application of cutting stock to solve the problem of cutting aluminum coils with high length variability. It aims at minimizing waste, balancing machine load and meeting customer demands.

Marsi and Warburton (1998) reported an analysis and improvement of aluminum extrusion at Alcan Vancouver Works, Canada. Aluminum extrusion in an extrusion plant is a special application of the cutting stock problem. There are a set of customer orders. The customer requirements in a few of the orders may vary - for distinct billet lengths or for billets of each type. An integer programming model is presented to maximize the yield.

The considerations in the system that were suggested for possible future improvements are -

1. the possibility of increasing yield by optimizing over a finer grid than 10mm grid,
2. the usefulness of historical order data to estimate yield maximizing billet lengths for unknown future order sets, and
3. given the plant set up, how the yield can be improved by keeping more billet lengths in stock.

Design Applications

An interesting model for the cell assignment problem (assigning output of cells to oven batches) has been developed by Gaillard, Yano, Leung et al. (1999) which is solved for maximization of expected revenue which depends mainly on the amounts of iron and silicon impurities in produced aluminum expressed in parts per million. Revenue of each batch is based on the levels of the two impurities in the output. Optimal and heuristic solution approaches are developed for deterministic version of the problem (known amount of impurities) and used as a basis for a heuristic procedure for the stochastic version. These procedures are recommended for process design and control as well, so that the ultimate impact of the changes in technological coefficients on the overall profit of the organization can be evaluated.

Production Planning

Based on production planning optimization, the first model that was developed was an integrated mathematical model. This model by Nicholls and Hedditch (1993) evaluates the impact of technological, organizational and financial changes on the strategic planning of different manufacturing units of Portland Aluminum Smelter and on overall smelter operations. This model takes into account many non-linear feedback loops that exist within the production process as well as electricity and Setting Cycle (SC) of the anodes. Some of the changes considered include capacity variations and rate (electric current) variations. The constraints are related to usage and availability of resources and capacities. The mathematical model is a sequential linear programming approach, where the first layer deals with given resources to maximize the output of aluminum and the second layer deals with the SC as its variable. The issues addressed by the model are:

1. Overall impact of business unit decisions on the total plant performance
2. Impact of changes in inventory and supply on the e financial performance
3. Impact of breakdowns and poor operation on the plant operations a
4. Impact of plant improvements on performance of the plant
5. Impact of changes in process costs on overall cost of manufacturing

Continuing his work on production planning optimization, Nicholls developed a mathematical model for ingot mill operations. The model was formulated to maximize the throughput of the mill under varying percentage time availability of furnaces, troughs and castors due to maintenance schedules and unexpected breakdowns .This model enabled the operations of the ingot mill to be optimized on a shift basis. The mathematical model for the anode plant assisted in production planning and controlling.

These mathematical models were further developed to aim at planning and scheduling of production in an aluminum smelter. The model tries to determine the optimal level of operations in an anode plant which is a very highly constrained area. The one day planning model reported by Nicholls (1995) is replicated for up to a month ahead and is interconnected by opening and closing stocks.
In the same year, Nicholls presents a nonlinear bi-level programming model of an aluminum smelter. This model of Nicholls (1995) encompasses all the areas of the smelter which operate in a multilevel way. This paper also presents a detailed development of mathematical modelling representation of an

aluminum smelter at Portland together with an discussion on the of algorithm to solve it. A global optimum was obtained by this algorithm.

More attention was paid to production planning optimization, with the development of an integrated model for reduction cells (RC) in an aluminum smelter. The model presented by Rodrigo, Renuka and Nicholls (1996) gave a better understanding of the operations of a reduction cell in a real time industrial situation. The model determined the optimal environment for the maximization of efficiency of RC. Typically the type of model used in RC depends on its nature with respect to reliability of its operation, data reliability and availability.

A medium-term planning and process improvements model has been developed by Balakrishnan and Brown (1996) for metal forming operations in aluminum tube manufacturing. This model helped in selecting standard extrusion sizes, and adopting proactive process improvement strategies that focus on critical constraints.

Another nonlinear bi-level programming approach was discussed for the integrated production of an aluminum smelter by Nichollas (1997). The model provided management with the ability to determine optimal operating values and evaluate capital expansion plans.

A Taguchi approach is described by Khoei, Gethin and Masters (1999) in order to optimize the aluminum recycling process. It determines the effect of different factors by computing simple averages and determining the optimum factor configuration. It also identifies the factors to which the recycling process is most sensitive.

A multi period nonlinear bi-level model of an aluminum smelter was designed by Nichollas (2000). This model allows for the transfer of stocks of raw materials throughout the planning period.

Decision Support System (DSS)

An optimization based DSS with a spreadsheet user interface was reported by Katok and Ott (2000).The DSS helped VMC (Valley Metal Corporation) to determine the weekly aluminum production schedule, and meet the brewery demand. The application of the DSS resulted in cost cutting at VMC.

developed by Dutta et al. (2011) present a model on multi-period production planning in an Indian aluminum company. Application of the DSS based on real data demonstrated a significant potential for improvement in (contribution to) profits. The model is capable of multiple horizons including strategic, technical and operational.

Caux, David and Pierreval (2006) studied the relevance of standard software packages like Advanced Planning and Scheduling (APS) System in the areas of casting and rolling in the aluminum conversion industry.

Scheduling

Bowers, Kaplan and Hooker (1995) describe a two phase scheduling model for an electromagnetic ingot casting process in the aluminum industry. The application of the model at the ingot production facility of a leading US aluminum manufacturer resulted in lower average inventory levels and a decrease in ingot misapplication/import from 20.4% to 0.4% of corresponding production.

Another interesting model was a mathematical model described by Stauffer and Liebling (1997) for an aluminum rolling-mill. This model presents an efficient rolling horizon scheduling algorithm based on Tabu search. This system was implemented in the plant, passed the testing phase, and was found to yield very satisfactory results.

Gravel, Price and Gagne (2000) discussed a genetic algorithm based approach to solve an industrial scheduling problem. The study describes the best processing sequence for ‘n’ orders and ‘m’ parallel machines. A double loop genetic algorithm is suggested to include the objectives to minimize the unweighted total lateness for all orders, the total set-up time over the planning horizon, and the total consumption of the daily production of refined molten aluminum. The problem was defined in two phases to determine the order assignments to furnaces and to determine the sequence of orders.

Continuing their work of addressing the industrial scheduling problem in an aluminum casting center, Gravel, Price and Gagne (2002) developed an ant colony optimization metaheuristic. This model efficiently represented a continuous horizontal casting process which takes into account a number of objectives that are important to the scheduler. This model has been implemented in an aluminum plant.at an Alcan aluminum foundry located in the Saguenay region of Québec, Canada.

The problem of scheduling was further addressed by Yin, Zou (2011) whereby they established a model of virtual enterprise's task scheduling in aluminum industry. This model takes into account the particle swarm optimization (PSO) algorithm approach. The results of the model show an improvement in optimization in allocation of resources and energy saving.
A genetic algorithm and integer programming based model was designed by Jensson, Kristinsdottir, and Gunnarsson (2005). The model was designed to address the problem of determining the sequence to cast aluminum ingots such that setup times are minimized. The genetic algorithm approach demonstrated improved results in the industrial implementation.

Gagne, Gravel and Price (2000) presented an ant colony heuristic solution for an industrial scheduling problem in an aluminium casting centre. The model takes into account multiple objectives involved in the casting process and hence minimizes the total tardiness.

6.3 Models based on Simulation

Two simulation models were developed by Arer and Ozdemirel (1999) and applied in an aluminum sheet producer factory in Istanbul, Turkey. Capacity expansion and sequencing alternatives were evaluated in this model with the objective to satisfy demand, balancing the process loads, and to keep the work-in-process inventory under control.

Another model in simulation environment for the aluminum rolling industry was formulated by Papanagnou and Halikias (2011). This model provides effective scheduling in aluminum coil production plants which are characterized by complexity.

6.4 Models based on Network Dynamics

The authors Li, Bathelt (2012) discuss a comprehensive tri-polar analytical framework of cluster evolution which is applied to the aluminum extrusion industry. This framework combines the three concepts of context, network and action. The model discusses a unique concept of network dynamics.

6.5 Models based on Forecasting

Blake (1979) describes a forecasting tool that predicts the purity of output from the chemical reduction process at an aluminum smelter, and assists in a decision between production and purchase. A FORTRAN programming based forecasting approach was developed to determine the number of tons of pure metal that can be produced as well as the average content of iron and silica. This method was able to return an accurate forecast because the process could be tracked easily.

6.6 Models based on Integrated Applications

An integrated application is the combination of one or more modeling problems of blending, designing, cutting stock, scheduling, production planning, simulation, or forecasting. In an integrated strategic and tactical planning model, the aluminum industry is characterized by two linear programming models. These integrated models solve the problem of resource allocation and the tactical problem of short range resource utilization.

6.7 Other Applications

In this section, we describe the various other models which are based on visual interactive modeling, dynamic benchmarks, and knowledge management.

A visual interactive model of Alcan Aluminum Company is discussed by Walker and Woolven (1991) from the. The model aims at reducing inventory, improving customer service and increasing output. This system calculates the production schedule very rapidly and presents the results in a variety of user readable format that brings the result from optimal solutions to implementation decisions.. These solutions on the user readable format helps the managers as they are very user friendly and are adapted in the model.

Warren and Nicholls (1999) discussed an approach to determine global forms of operations evaluation in the ingot mill of an aluminum smelter in Australia by. The paper depicts the overall running of the smelting plant and the work done by the authors assisted the management of the company with the quantification of benefit coming out of global operations management improvement.

An environmentally sustainable supply chain optimization model is described by Ferretti, Zanoni, Zavanella et al. (2007). The model evaluates the economic and environmental effects of the aluminum supply chain. The model aims at determining the optimal quantity of supply of aluminum mix, that is, molten and solid alloy which is capable of balancing the economic benefit in terms of financial results and environmental benefits in reduction in emissions .

Nichollas and Cargill (2008) developed a knowledge management tool which could handle the difficulties associated with a production process that is explained by a model with a fuzzy contained a fuzzy sub process. It targets the electrolytic process of alumina in smelting process because the impact of such sub processes on production is significant.
The fabrication process in the aluminum industry which generates waste is modeled using a mathematical model developed by Hajeeh (2010).

The model used actual data from an aluminum fabrication industry, and showed that considerable savings could be realized through a scientific approach of using and implementing mathematical OR/MS with an objective of minimizing environmental waste.

7. Possible Research Work in OR/MS in Aluminum Industry

From our discussion on the aluminum industry and survey of OR/MS models, we identify multiple areas for research. Here are some potential areas for future research:

1. Aluminum is a power intensive industry. A possible extension could be in the area of optimum use of power like in the steel industry(Dutta et al., 1994 and Sinha et al., 1995). Another area could be to model the power crisis during peak power demand situations.

2. Selection of available power resources (including renewable energy resources) for overall cost minimization, economic viability of building a captive power plant with optimum capacity having objectives of matching the producer's requirements as well as cost minimization.

3. The OR/MS research on blending in production and smelting can result in a significant impact on an organization's bottom line. An optimal blending mix can fetch profits from high demand and high margin finished aluminum

4. Supplier selection is an important area of OR/MS research if a company is importing aluminum ore and aluminum products from another country. The issues in modeling are the cost of transportation, the type of raw material (% of aluminum in the ore), taxes imposed by the exporting country, the purchase price of aluminum ore and products, etc.

5. Another possible research area is scheduling the recycling of aluminum from scrap using the same capacity without affecting the present schedule for primary metal production.
6. Selection of optimum policy for processing of byproducts - whether they have to be produced in the plant or outsourced or whether to sell it as raw material to other producers.

7. There is not much reported research on DSS application in aluminum industry. Application of optimization based DSS is a wide area of research. The application of DSS can be studied in smelting, production planning, scheduling, blending, cutting stock, etc.

8. Researchers can study the series of mathematical models reported and published by Nicholls in Portland Aluminum Smelter, Australia to replicate them in other geographies.

9. This study does not find much reported research on integrated supply chain planning and modeling in the aluminum industry. There is scope to conduct research for outbound logistics, inbound logistics, and integrated supply chain planning.

8. Conclusion

This paper has presented a compiled survey of many operational research models formulated for the aluminum industry. This survey is motivated by the need for innovation in the emerging modern aluminum industry. The implementation of OR/MS in the aluminum industry can help enhance manufacturing functions, reduce production costs, and provide higher quality products which will make a huge economic and sustainable impact on the bottom line of the company. As per our survey, the estimated world aluminum production in 2012-2013 is 45 million ton (MT) and the price of aluminum per ton as estimated by LME is $1976. Hence the annual revenue generated by the aluminum industry becomes $89.32 billion in the world economy. Even a small investment of possibly 1% of the total generated revenue towards the application of OR/MS can lead to significant improvement in the profits realized by aluminum companies. The survey of OR/MS techniques in this study illustrated that the practices adopted by VMC (Valley Metal Container) helped it reduce direct costs by over $150,000 per year. Similarly cyclic planning in 1996 helped Alcan Vancouver to increase its output from 101,200 pounds per month to over 121,400 pounds per month. Nicholls, in a series of his publications on optimization in production planning and scheduling at Portland Aluminum Smelter, Australia demonstrated the impact of OR/MS. Therefore we can conclude that the survey unveils the scope for potential models which will not only help in tapping the vast economic and sustainable benefits, but also bring out the gaps which researchers can address.

Appendix A: Classification of OR/MS tools in aluminum companies

Technique	Mining	Smelting	Metal Forming			Production Planning	Environment
			Casting	Rolling	Extrusion		
Scheduling			**5**	**33**		**37**	
			9				
			11				
			12				
Blending	**7**	**20**					
Design			**4**				
Production Planning		**21**		**31**			
		22					
		23		**2**	**16**		**17**
		24					
		25					
		26					
		30					
Advanced Planning & Scheduling			**6**				
Cutting Stock					**32**		
					14		
					35		
Simulation			**1**	**28**			
Network Dynamics					**29**		
Decision Making		**3**					
Integrated Application		**15**					
Visual Interactive Models				**34**			
Dynamic Benchmarking		**36**					
Knowledge Management		**27**					
Supply Chain Model							**9**
Mathematical Modeling							**13**

Appendix B: World aluminum production ('000 metric tons)

Year	China	North America	Central & East EUR	GCC	West Europe	Asia (ex China)	Oceania	South America	Africa	Est. Un-reported	Total ('000 MT)
2012	19,754	4,851	4,323	3,662	3,605	2,535	2,186	2,052	1,639	600	45,207
2011	17,786	4,969	4,319	3,483	4,027	2,533	2,306	2,185	1,805	576	43,989
2010	16,131	4,689	4,253	2,724	3,800	2,500	2,277	2,305	1,742	732	41,153
2009	12,964	4,759	4,117	NA	3,722	4,400	2,211	2,508	1,681	624	36,986
2008	13,105	5,783	4,658	NA	4,618	3,923	2,297	2,660	1,715	732	39,491
2007	12,588	5,642	4,460	NA	4,305	3,717	2,315	2,558	1,815	732	38,132
2006	9,349	5,333	4,230	NA	4,182	3,493	2,274	2,493	1,864	720	33,938
2005	7,806	5,382	4,194	NA	4,352	3,139	2,252	2,391	1,753	636	31,905
2004	6,689	5,110	4,139	NA	4,295	2,735	2,246	2,356	1,711	576	29,857
2003	5,547	5,495	3,996	NA	4,068	2,475	2,198	2,275	1,428	504	27,986
2002	4,321	5,413	3,825	NA	3,928	2,261	2,170	2,230	1,372	636	26,156
2001	3,371	5,222	3,728	NA	3,885	2,234	2,122	1,991	1,369	588	24,510
2000	2,794	6,041	3,689	NA	3,801	2,221	2,094	2,167	1,178	672	24,657

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