



NTNU – Trondheim
Norwegian University of
Science and Technology

Stock-Driven, Trade-Linked, Multi-Regional Model of the Global Aluminium Cycle

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MASTER THESIS

for

Shyaam Ramkumar
Spring 2014**Stock-Driven, Trade-Linked, Multi-Regional Models of the Global Aluminium Cycle****Background and objective**

Global Aluminium Models have been developed primarily as tools for informing decisions on recycling and have been extended significantly to better understand the entire aluminium system. To get a more detailed picture of the global aluminium cycle, the student developed in his project a trade-linked, multi-regional mass flow model of the global aluminium cycle for 10 regions across a 50-year period from 1962 to 2011. Through these models, we were able to understand the historical flows of aluminium and the roles of various regions in the aluminium cycle to uncover patterns of aluminium production, consumption, recycling, and regional trade.

The goal of this thesis is to use these models as a foundation to develop stock-driven models that are able to predict the future demand among the various aluminium products. Utilizing insights from the historical, trade-linked, multi-regional models of the global aluminium cycle developed in the NTNU Masters Project, the Masters Thesis will determine future aluminium flows through stock-driven, trade-linked, multi-regional models across the 10 regions defined in the Masters Project study over a 40 year period from 2012 to 2050.

The Masters Thesis aims to answer the following questions:

- What is the future demand for aluminium products and the future availability of scrap given the stock dynamics of final product consumption?
- How can future production of aluminium products meet this demand given the following Production Capacity Scenarios?
 - future production capacity is built up domestically in each region to meet consumption demand and minimize transport (import) of final products
 - future production capacity is built up in mining regions to minimize transport of raw materials
 - future production capacity is built up in regions with low energy prices
 - future production capacity is built up according to the historical trend

The following tasks are to be considered:

1. Conduct literature review of projected future changes in demand for defined final product categories
2. Update the historical, trade-linked, multi-regional models with new assumptions or data as necessary
3. Refine the historical, trade-linked, multi-regional model framework to incorporate a stock-driven approach for years 2012 to 2050 and simplify the system definition
4. Model projected future demand for aluminium in final product categories based on literature review and stock dynamics
5. Model projected future scrap outflows based on stock dynamics in final product categories
6. Model projected future mining levels based on analysis of historical mining levels and trends
7. Incorporate global market mechanisms in stock-driven model to account for projected future trade flows within the different scenarios
8. Model future trade flows based on mass balance consistency and historical trends for trade of different products by each region
9. Develop lifetime distribution functions for production to model and test the 4 Production Capacity Scenarios defined above
10. Analyze future flows within the global aluminium cycle under each Production Capacity Scenario
11. Interpret findings in terms of strategy implications for the aluminium industry for development of future aluminium production capacity to 2050
12. Write the thesis report

Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment

represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

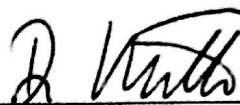
The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

- Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
 Field work

Department of Energy and Process Engineering, 14. January 2014



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Abstract

Future consumption and use of aluminium is expected to continue to increase significantly. However, due to the heavily inter-connected and complex global aluminium system, there is a need to better understand how increases in aluminium consumption and demand will impact the future flows within the global aluminium cycle. This study aims to analyse the historical flows and in-use stock of aluminium within each region to create a stock-driven, trade-linked, multi-regional model that can forecast global aluminium flows to 2050 through various scenarios. The end goal of this research effort is to provide the aluminium industry with a robust tool that provides insights into long-term business strategies given various possibilities for how the global aluminium cycle could evolve in the future.

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1. Introduction

Aluminium is the third most abundant element in the Earth's crust after oxygen and silicon. Following its discovery in the 1800s and commercial production in the 1880s, aluminium has grown to be the second most used metal in the world following iron. The metal's durable, lightweight, flexible, and corrosion resistant properties have led to a significant increase in use for a variety of applications in construction, transport, packaging, and electronics.

The use of aluminium is expected to continue to increase in the future. The USGS estimates that global aluminium consumption will increase by almost 2.5 times by 2025 compared to 2006 levels, with most of the aluminium consumption occurring in countries that did not consume as much aluminium in the past, such as China, Russia, Brazil, and India. As production and consumption are two sides of the same coin, a significant increase in aluminium, alumina, and bauxite production is necessary to meet the global consumption demand for aluminium. In addition, there will also be a significant increase in scrap and secondary aluminium as the consumption of aluminium increases in the future, given the lifetimes of different aluminium containing products (Menzie, 2010). Due to the heavily inter-connected and complex global aluminium system, there is a need to better understand how increases in aluminium consumption and demand will impact the future flows within the global aluminium cycle.

Material Flow Analysis is a widely used approach to develop models that map complex systems and uncover the intricate system of flows within them. Several studies have been performed using this approach to map the global aluminium cycle. The GARC (2011) model, developed by the International Aluminium Institute is the first dynamic model of global aluminium flows, and has since been updated to capture flows as recent as 2011, though it does not account for regional flows. More detailed regional studies on aluminium flows have also been conducted, primarily static models for a specific year for specific countries, such as Europe (Bertram, Martchek, & Rombach, 2009), China (Chen & Shi, 2012), Japan (Hatayama et. al., 2009) and the United States (Liu, Bangs, & Mueller, 2011).

However, the majority of these studies have not been developed to effectively forecast future flows within each region using a stock-driven approach, one that focuses on the future aluminium consumption within society and evaluates the impacts of that future demand on the rest of the aluminium cycle. The GARC (2011) model attempts to forecast future global flows by using estimated growth rates for semi-fabricated net shipments, but this approach

does not take into account consumption or in-use stocks of aluminium. The study conducted by the USGS (Menzie, 2010) to forecast the future aluminium industry to 2025 uses regression analyses with GDP and aluminium consumption per capita to project future aluminium consumption in different countries around the world. Similarly, a study by Liu, Bangs, and Mueller (2013) on the stock dynamics of the global aluminium cycle forecasts global aluminium in-use stock per capita based on various saturation levels. A more regional report developed by the European Aluminium Agency (2012) forecasts European aluminium consumption and scrap availability to 2050. None of these studies, however, evaluate the implications of future consumption on aluminium, alumina, and bauxite production and the global aluminium cycle.

Thus, there is no comprehensive model that sufficiently forecasts future aluminium consumption using a stock-driven approach and evaluates the implications of future consumption on primary and secondary aluminium production, alumina, and bauxite in different regions within the global aluminium cycle. Recent studies by NTNU and the International Aluminium Institute have developed historical, trade-linked, multi-regional models to understand the dynamics of the global aluminium cycle for various product categories within each region from 1962 to 2011 (Ramkumar, 2013). This study aims to build upon these historical models to analyse the historical flows and in-use stock of aluminium within each region to create a stock-driven, trade-linked, multi-regional model to forecast global aluminium flows to 2050 through various scenarios. The end goal of developing such a model is to provide the aluminium industry with a robust tool that provides insights into long-term business strategies given various possibilities for how the global aluminium cycle could evolve in the future.

In order to highlight how the stock-driven, trade-linked, multi-regional model can be used for scenario analysis and strategy development, this paper aims to use the model to answer the following questions using a defined set of scenarios developed in cooperation with the International Aluminium Institute and the aluminium industry:

1. *What is the future demand for aluminium products and the future availability of scrap given the stock dynamics of aluminium consumption in different regions within the different final product categories?*
2. *How can future production of aluminium and fabrication of final products meet this demand given the following 4 scenarios?*
 - ***Middle East dominates primary AL production, Fabrication follows domestic demand:*** *By 2050, future primary aluminium production is dominated by the*

Middle East, with other regions' primary aluminium production capacity not replaced. By 2050, fabrication of final products containing aluminium is satisfied by domestic facilities that meet domestic demand.

- ***Middle East dominates primary AL production, Fabrication integrated with primary AL production:*** *By 2050, future primary aluminium production is dominated by the Middle East, with other regions' primary aluminium production capacity not replaced. Fabrication of final products containing aluminium is integrated with primary AL production facilities.*
- ***China dominates primary AL production, Fabrication follows domestic demand:*** *By 2050, future primary aluminium production is dominated by China, with other regions' primary aluminium production capacity not replaced. By 2050, fabrication of final products containing aluminium is satisfied by domestic facilities that meet domestic demand.*
- ***China dominates primary AL production, Fabrication integrated with primary AL production:*** *By 2050, future primary aluminium production is dominated by China, with other regions' primary aluminium production capacity not replaced. Fabrication of final products containing aluminium is integrated with primary AL production facilities.*

2. Methodology

The stock-driven, trade-linked, multi-regional model represents a fundamental shift in thinking for how the aluminium industry can understand and evaluate future flows within the global aluminium cycle. The GARC model (2011) and previous historical models (Ramkumar, 2013) used by aluminium industry have focused on a production-driven approach, evaluating the impact of shipments of aluminium on the rest of the industry. However, the stock-driven model focuses on analysing in-use stock within society and takes a more demand oriented approach in forecasting future aluminium flows. In this way, the stock-driven model evaluates historical consumption of aluminium, future demand for aluminium, production to meet this demand, and the implications for the global aluminium cycle. This section will describe the methodology behind developing the stock-driven, trade-linked, multi-regional model.

2.1. System Description

The first step taken in creating a stock-driven model that forecasts the future of the global aluminium cycle was to determine the timeframe. According to a paper by Spyros Makridakis, long-term forecasting is crucial for identifying potential opportunities and threats to the business environment. Compared to short-term and medium-term forecasting, which have higher uncertainty and less useful insights, long-term forecasting is where real strategic benefits can be extracted (Makridakis, 1996). As a result, the stock-driven, trade-linked, multi-regional model continues where the historical models left off and forecasts the aluminium cycle by an additional 39 years – from 2012 to 2050. This provides a smooth continuation of both historical data and future trends and is a sufficiently long time horizon for strategic forecasting and scenario planning.

In an effort to maintain consistency with the historical models as well as utilize historical trends to aid in future projections, the regions defined in the stock-driven model are the same as those defined in the historical, trade-linked, multi-regional models (Ramkumar, 2013). The 10 regions considered within the global aluminium cycle are shown in table 1.

Table 1. List of 10 Regions in Model

10 Regions Modeled in Study
Europe
North America
Latin America & the Caribbean
Africa
Middle East
China
India
Rest of Asia
Australia & Oceania
USSR

As was the case with the historical, trade-linked, multi-regional model study (Ramkumar, 2013), there are slight differences between the regions defined here and the GARC (2011) model typically used by the aluminium industry. One of the main differences between this study's regional classification and the data used in the GARC (2011) model is the inclusion of the Middle East countries into a separate region. There are also minor differences between the countries that are categorized as Europe in the GARC (2011) model and in the stock-driven model. A detailed list of the countries classified into the various regions can be found in the model Excel-file under the tab "Country Categorization."

The processes defined in the stock-driven, trade-linked, multi-regional model are also similar to the ones defined in the historical model (Ramkumar, 2013), but with slight modifications to make the model simpler and easier to use. The following is a brief summary of the global aluminium cycle, which along with the system outlined in the GARC (2011) and additional input from the International Aluminium Institute, formed the basis for the system definition in the historical, trade-linked, multi-regional models (Ramkumar, 2013):

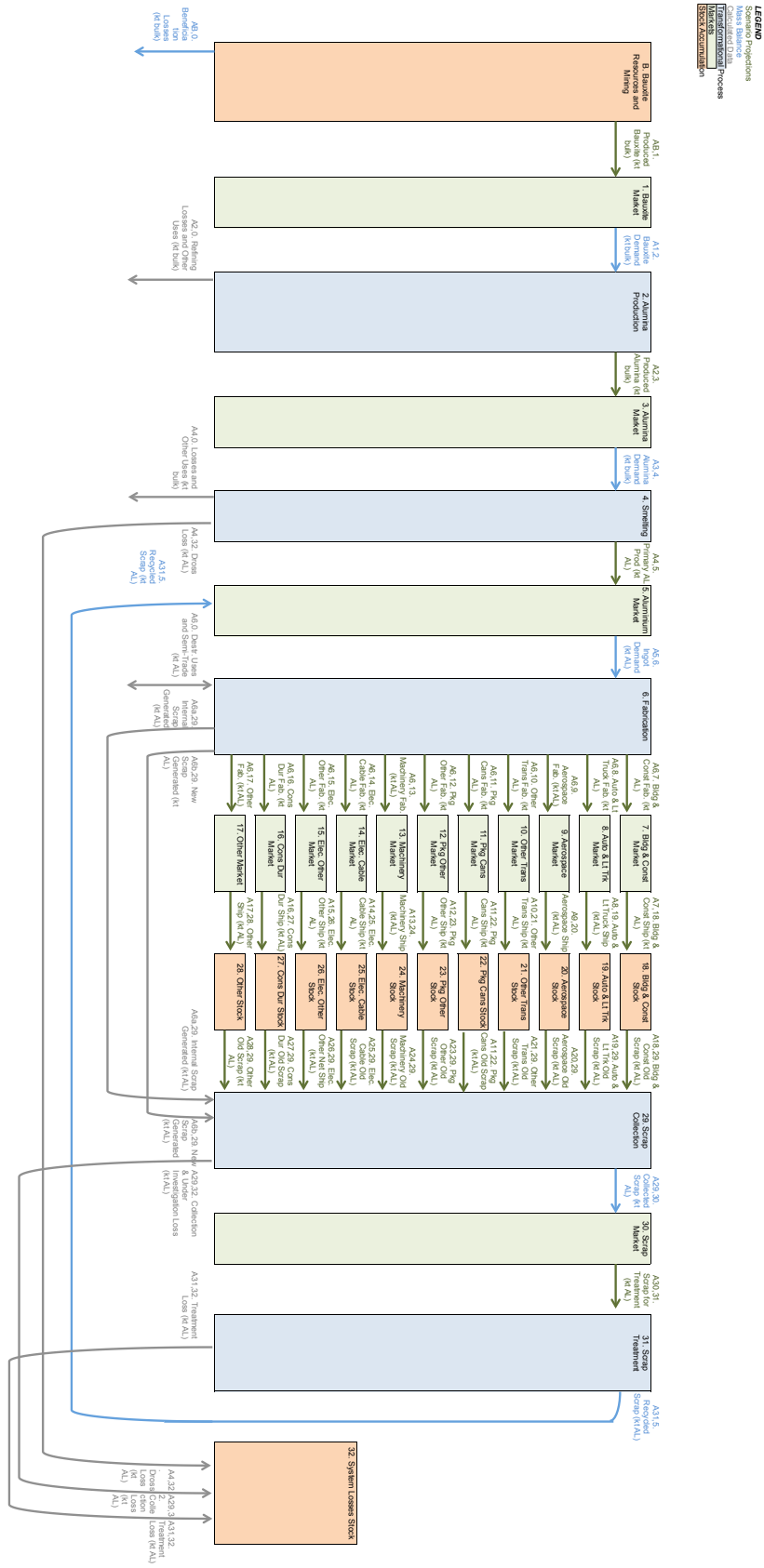
- The first step in the global aluminium cycle is the mining of bauxite ore, which goes through a beneficiation process to remove impurities and dried before it is shipped to the alumina refinery (Luo & Soria, 2007).
- At the refinery, the bauxite is put through the Bayer process, the most widely used and efficient process for alumina manufacturing, to create alumina (Luo & Soria, 2007).
- Next, the alumina is sent to smelters, which use the Hall-Héroult process to convert alumina to aluminium ingots through electrolysis (Luo & Soria, 2007).
- The aluminium ingots then undergo rolling, extrusion, casting, and other processes to produce semi-fabricated products (Liu & Mueller, 2012).
- These semi-fabricated products are sent to manufacturers to be used as components for the production of final products in different industries (Liu & Mueller, 2012).
- In the use phase, the various final products have different lifetimes and as these products become obsolete, they are collected for recycling (Liu & Mueller, 2012).
- The scrap goes through a variety of treatment steps to clean the scrap, after which it is re-melted and refined to produce secondary aluminium. In addition, new and internal scrap from the semi-manufacturing and final product manufacturing processes are also collected and re-melted to produce secondary aluminium (Luo & Soria, 2007).

Figure 1 provides a general overview of the system defined in the stock-driven, trade-linked, multi-regional model. Like the GARC (2011) model and the historical, trade-linked, multi-regional models (Ramkumar, 2013), the upstream processes related to Bauxite and Alumina are displayed as metric kilotons of bulk bauxite and bulk alumina. However, all the processes after primary aluminium production are displayed as metric kilotons of AL. Much of the flows are similar to the historical models (Ramkumar, 2013) in order to maintain consistency between historical data and future projections

However, there are some key differences between the historical models (Ramkumar, 2013) and the stock-driven model. These changes were made in order to simplify the model for user-friendliness and forecasting purposes:

- Semi-fabrication and final product fabrication processes and relevant flows were combined into a single process called “Fabrication.”
- The separation of the 4 different aluminium products - rolling, extrusion, casting, and semi-other - was aggregated; however, the separation of flows into 11 final product categories was maintained.
- Scrap treatment was simplified into a single treatment step that combines pre-melting and remelting.
- Unlike the historical models (Ramkumar, 2013), which show trade in detail between each region, trade in the stock-driven model is treated as a global market. Each of the producing regions for a particular resource contributes to a global market pool, from which consuming regions can draw to meet demand. Thus, the regions are still trade-linked, but there is no way to know the imports and exports of different resources between each region.

Figure 1. Stock-Driven Model System Overview



As figure 1 shows, the processes in the system are color-coded and classified according to the following categories:

- **Transformational Processes:** processes that transform or convert inputs into a different set of outputs
- **Markets:** processes that represent the global market inventory of a produced resource and the global demand and consumption of that resource
- **Stock Accumulation:** processes that accumulate a stock of the inflows over time

Similarly, the flows in the system are color-coded and classified according to the following categories:

- **Scenario Projections:** flows determined through scenarios developed to answer specific questions or through projections based on historical trends
- **Calculated Data:** flows determined through transfer coefficients and specific data points, such as collection rates, utilization rates, loss rates, etc.
- **Mass Balance:** data calculated using the Mass Balance principle, such that input flows are equal to output flows plus any stock accumulation

Though this is not represented in Figure 1 above, each of the flows in the stock-driven, trade-linked, multi-regional model is broken down by region. So for a given year, the model shows the total global flow values between the various processes and also how the flows are distributed by region. The assumptions used to calculate the flows for each region will be discussed in section 2.2.

2.2. Scenario Projections and Model Assumptions

In a paper by Bradfield et al. (2005) tracing the origins of scenario planning as a strategic planning tool, it notes that in order to accurately support decision making, models of future environments needed to be able to investigate various alternatives and their consequences. This led to the use of scenarios as a methodology for planning in complex and uncertain environments (Bradfield et al., 2005). Thus, in order for the stock-driven, trade-linked, multi-regional model to be used as a tool for strategic decision making, it must be able to answer various strategy questions that are relevant to the aluminium industry through the use of scenarios to evaluate various alternatives for the future of the aluminium industry and their consequences. The following sub-section will highlight the defined set of scenarios and assumptions that the stock-driven model analysed to answer the two questions posed in this paper.

2.2.1. In-Use Stock Scenario Projections

As a stock-driven model, it is first necessary to understand how the in-use stock and aluminium consumption will evolve in the future. Forecasting future aluminium consumption and demand to answer the first strategic question has a high degree of uncertainty. There are a variety of factors within each of the 10 regions and within each of the 11 final product categories that could significantly alter the way aluminium could be consumed in the future. Government regulations, trade policies, new products using aluminium, substitute materials, etc. are some of the many factors that could influence future aluminium demand.

Rather than accounting for all of these different possibilities and creating a multitude of scenarios of the future of aluminium demand, this paper used in-use stock dynamics as an indicator for aluminium consumption and analysed historical data to forecast how the in-use stock could evolve based on trend-based projections. The approach follows a similar approach used by Liu, Bangs, & Mueller (2013), which estimates future aluminium demand using in-use stock per capita. Only one scenario for future aluminium demand projections was assumed for simplicity, as the main objective of this paper is to highlight how such a model can be used to forecast future aluminium flows and develop strategies to meet a given level of future demand.

Table 2. Approach for Forecasting Stock Dynamics

	Product Shipments	Availability of Old Scrap	Stock Change	In-Use Stock Per Capita	In-Use Stock
Historical Data (1950-2011)				1	
Forecasted Data (2012-2050)	6	5	4	2	3

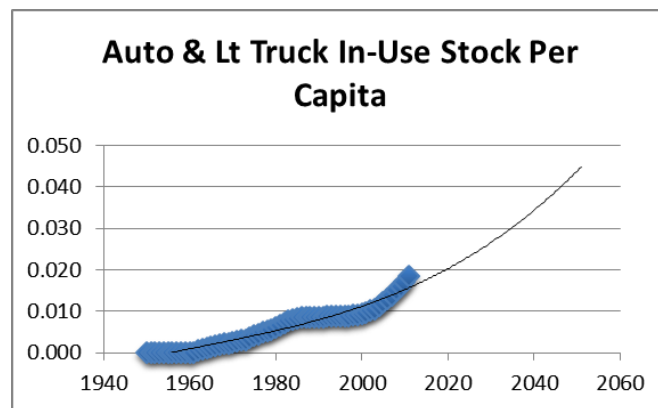
The approach is illustrated in Table 2 above and each of the steps taken is described in detail below:

1. The first step was to look at the in-use stock of aluminium built up within each of the 10 regions and 11 product categories from 1950 to 2011 using the previously developed historical models (Ramkumar, 2013). This data was then divided by population estimates for each region from 1950 to 2011 using the United Nations Population Division's World Population Prospects (UN, 2013) to calculate in-use stock of aluminium per capita historically. For the packaging categories, "Packaging Cans" and "Packaging Other," the in-use stock of

aluminium per capita was calculated from 1962 to 2011 due to how the data was calculated in the historical models (Ramkumar, 2013).

2. Next, the in-use stock of aluminium per capita for each of the 11 product categories within each of the 10 regions was plotted in a chart and Excel's trendlines option was used to forecast the data to 2050. The trendlines use regression analysis to find a line of best fit through linear, logarithmic, polynomial, power, or exponential functions, then uses these functions to find future values until 2050. Figure 2 shows an example of the historical in-use stock of aluminium per capita and a polynomial trendline forecasted until 2050 for the Auto & Lt Truck product category for the Middle East region.

Figure 2. Middle East Auto & Lt Truck In-Use Stock Per Capita (tons per capita)



Using the trendlines as a guide, the order of magnitude of the in-use stock of aluminium per capita in 2050 compared to historical levels was determined. Thus, using the example in figure 2, Auto & Lt Truck in-use stock of aluminium per capita for the Middle East in 2050 is expected to be around 0.045 tons per capita, which is 225% of 2011 levels based on historical trends. The in-use stock of aluminium per capita in 2050 was thus determined for all of product categories in each of the regions. Table 3 shows the assumptions for in-use stock of aluminium per capita in 2050 compared to 2011 levels for the 11 product categories for all 10 regions. This can be viewed in the "Scenarios and Inputs" tab in the model's Excel file.

Table 3. 2050 In-Use Stock of Aluminium per Capita Compared to 2011 Levels

Final Product Category	Europe	North America	Latin America	Africa	MidEast	China	India	Rest of Asia	Australia Oceania	USSR
Building & Construction	150%	105%	170%	150%	230%	350%	380%	130%	150%	350%
Auto & Lt Truck	140%	150%	275%	160%	225%	350%	380%	175%	175%	350%
Aerospace	150%	150%	150%	95%	150%	420%	130%	130%	155%	500%
Other Transportation	160%	130%	175%	160%	180%	280%	320%	180%	300%	170%
Packaging - Cans	160%	80%	350%	140%	150%	150%	100%	200%	500%	300%
Packaging - Other (Foil)	180%	130%	145%	120%	200%	250%	350%	250%	130%	120%
Machinery & Equipment	140%	130%	200%	175%	220%	275%	500%	115%	150%	105%
Electrical - Cable	165%	105%	180%	150%	160%	290%	265%	105%	135%	105%
Electrical - Other	165%	120%	250%	220%	240%	375%	300%	165%	250%	375%
Consumer Durables	145%	150%	200%	250%	300%	550%	300%	300%	250%	400%
Other (ex Destructive Uses)	145%	150%	150%	120%	115%	180%	120%	160%	150%	40%

Though the trendlines construct a line of best fit using linear, logarithmic, polynomial, power, or exponential functions, these functions have different rates of growth before reaching the forecasted 2050 levels. However, as in the paper by Liu, Bangs, & Mueller (2013), this paper assumed that the in-use stock of aluminium per capita for the 11 product categories within the 10 regions would grow gradually before levelling off by 2050. In order to fulfil this assumption for how in-use stock per capita would grow between 2011 and 2050, this paper used a unique negative square function to estimate in-use stock of aluminium per capita between 2011 and 2050. Equation 1 provides the exact formula used to create the curve.

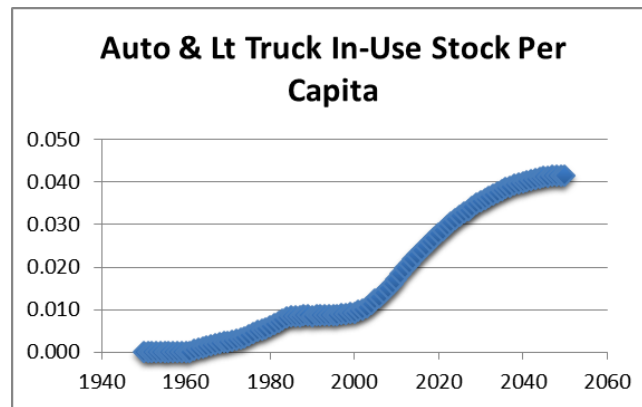
Equation 1. Negative Square Growth Formula In-Use Stock of Aluminium Per Capita

$$SPC_t = \frac{(SPC_{2050} - SPC_{2011}) * (t - 2050)^2}{-(2050 - 2011)^2} + SPC_{2011}$$

where SPC_t is the in-use stock per capita for year t from 2012 to 2050

Using the same example of in-use stock of aluminium per capita for the Auto & Lt Truck product category for the region Middle East, figure 3 shows both the historical data from 1962 to 2011, as well as projected data from 2012 to 2050 using the negative square growth formula. As the figure shows, there is a gradual growth in the in-use stock of aluminium per capita for the Auto & Lt Truck product category in the Middle East after 2012, before it levels off as it approaches 2050.

Figure 3. Historical and Projected Middle East Auto & Lt Truck In-Use Stock Per Capita (tons per capita)



3. The forecasted in-use stock of aluminium per capita for all of the 11 product categories within each of the 10 regions from 2012 to 2050 was then multiplied by population projections for each region from 2012 to 2050 to get in-use stock of aluminium. Future population projections from the United Nations Population Division's World Population Prospects were used, assuming the UN's medium fertility scenario. The medium fertility scenario was selected since it is the median of 60000 projected country trajectories and forms the basis for all the other possible scenarios for population growth that the United Nations Population Division analysed (UN, 2013).
4. Next, the change in stock between each of the forecasted years was calculated in a manner similar to the historical data (Ramkumar, 2013). Stock Change, ΔS , was calculated following the formula shown in equation 2.

Equation 2. Stock Change Calculation

$$\Delta S_t = (S_t - S_{t-1})$$

where ΔS_t is the stock change and S_t is the in-use stock for year t from 2012 to 2050

5. The future outflows of aluminium containing products within the 11 product categories for each of the 10 regions for 2012 to 2050 was also calculated using the same approach as the historical models (Ramkumar, 2013). The future outflows were based on a lifetime distribution of the final product categories, which calculates the percentage of the historical product shipment flows that become obsolete and thus become available as old scrap. This methodology was borrowed from the study conducted by Liu (2013). Equation 3 summarizes the calculation of future outflows.

Equation 3. Future Outflows Calculation

$$O_t = \int_{t_0}^t L(t, t') * PS(t') dt'$$
$$L(t, t') = \frac{1}{\sigma * \sqrt{2\pi}} * e^{-\frac{t-t'-m}{2\sigma^2}}$$

where O_t is the outflow for year t from 2012 to 2050,
 $PS(t')$ is the product shipments from previous years t' ,
 $L(t, t')$ is the lifetime function at year t given by a Normal distribution
with an average lifetime of m and standard deviation of σ

For the two packaging product categories, “Packaging – Cans” and “Packaging – Other,” the future outflows are calculated by the approach illustrated in equation 4.

Equation 4. Packaging Future Outflows Calculation

$$O_t = PS_{(t-m)}$$

where O_t is the outflow for year t from 2012 to 2050,
 $PS_{(t-m)}$ is the product shipments from the average lifetime m years prior

The average lifetimes and standard deviations used to calculate the future outflows from 2012 to 2050 for the 11 product categories were assumed to be the same as in the historical models for all the regions (Ramkumar, 2013) and the GARC (2011) model. These lifetimes and standard deviations are summarized in table 4. It should be noted that these lifetimes and standard deviations are based on fixed assumptions for all years, and they may contain a high degree of uncertainty, particularly as these lifetimes may change over time. However, these figures were used since they are widely accepted and agreed upon by the aluminium industry.

Table 4. Average Lifetimes and Standard Deviations for Outflow Lifetime Distribution

Final Product Category	Average Lifetime	Standard Deviation
Building & Construction	50	17
Auto & Lt Truck	20	6
Aerospace	40	13
Other Transportation	30	10
Packaging - Cans	1	
Packaging - Other (Foil)	1	
Machinery & Equipment	30	10
Electrical - Cable	30	10
Electrical - Other	30	10
Consumer Durables	12	4
Other (ex Destructive Uses)	20	7

6. Lastly, future product shipments for each of the 11 product categories in each of the 10 regions from 2012 to 2050 were calculated using the mass balance principle. The mass balance principle is described in equation 5 below and states that inflows into a process, in this case product shipments, must equal the outflows plus the change in stock.

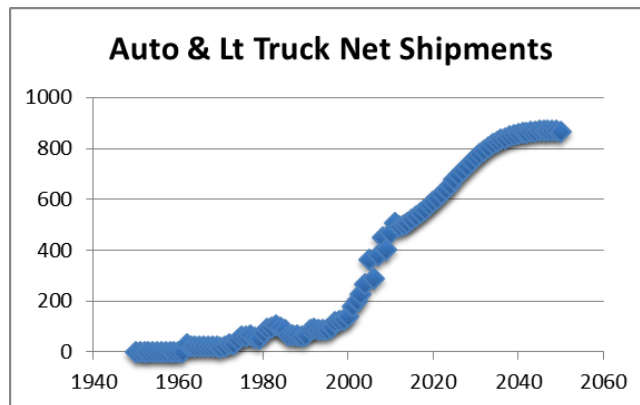
Equation 5. Future Product Shipments Calculation

$$PS_t = O_t + \Delta S_t$$

where PS_t is the product shipments, O_t is the outflows, ΔS_t is the stock change for year t from 2012 to 2050

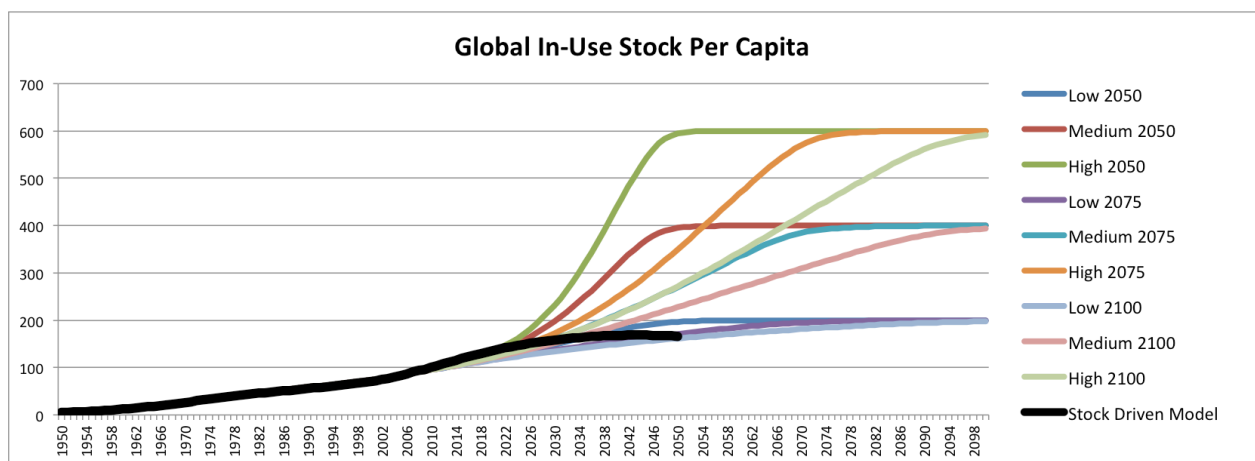
The assumptions made for forecasted 2050 in-use stock per capita for all the product categories and all the regions in step 2 were adjusted from the levels shown by the trendlines to ensure that historical shipments and future product shipments had a smooth transition and were in the right order of magnitude. Figure 4 shows the historical and future product shipments curve after adjustment for the Auto & Lt Truck product category in the Middle East.

Figure 4. Historical and Projected Middle East Auto & Lt Truck Product Shipments ('000 Metric Tons)



In order to ensure that the forecasted in-use stock of aluminium per capita numbers were within the range of previous studies, the global in-use stock of aluminium per capita calculated through the stock-driven model was compared with 9 scenarios developed in a paper by Gang Liu, Colton Bangs, and Daniel Mueller. As figure 5 shows, the stock-driven model's estimate for the growth of in-use stock of aluminium per capita is in line with the Low 2050, Low 2075, and Low 2100 scenarios developed by Liu, Bangs, & Mueller (2013). This is likely because the future in-use stock per capita forecasts based on historical trends are more conservative than the assumptions made in the 9 scenarios.

Figure 5. Global In-Use Stock Per Capita Stock Driven Model vs. Other Scenarios (kg/capita)



Thus, the model can evaluate one potential scenario to answer the first strategic question, “What is the future demand for aluminium products and the future availability of scrap given the stock dynamics of aluminium consumption in different regions within the different final product categories?” These assumptions can be viewed under the “UseStock”

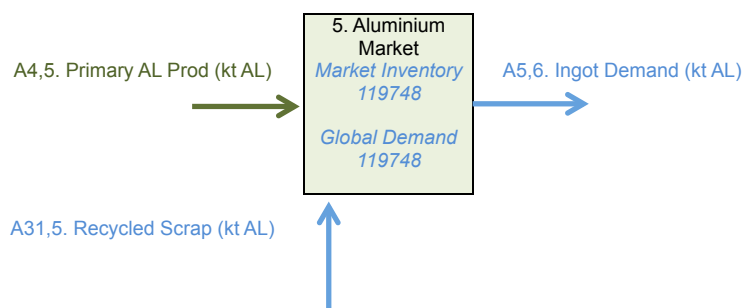
tabs for each region in the model's Excel file. This forms the basis for the stock-driven, trade-linked, multi-regional model. By understanding the future aluminium consumption, the context is set for developing scenarios to answer the second strategic question and understanding the implications of the forecasted future demand for the entire aluminium industry.

2.2.2. Satisfying Aluminium Demand Scenario Projections

In order to answer the second strategic question of how to satisfy future aluminium demand, the level of bauxite, alumina, primary vs. secondary aluminium, as well as the level of product fabrication for each of the 11 product categories in the 10 regions needs to be determined. Additionally, the role of the various regions and how primary aluminium production as well as product fabrication will be distributed across the 10 regions needs to be evaluated.

To address the first issue, the stock-driven, trade-linked, multi-regional model assumed a production follows demand approach, adapted from the capacity follows demand approach presented in a demand-driven model for steel capacity (Pauliuk et al., 2013). Thus, demand is always met by production – future global demand for aluminium containing products for any given year is completely satisfied by product fabrication, future global demand for primary aluminium for fabrication for any given year is completely satisfied by primary aluminium production, and so on for bauxite, alumina, and scrap. This is illustrated by figure 6 using the aluminium market in 2047 as an example.

Figure 6. Aluminium Market in 2047 Assuming Production Follows Demand



Evaluating the role of different regions and forecasting how the future production levels will be broken down across the 10 regions is more challenging. As was the case with future aluminium consumption, there could be a variety of factors that affect future flows in the aluminium production cycle in the different regions such as government regulations,

protectionist trade policies, financial considerations, etc. Starting with primary aluminium production and product fabrication, four simple scenarios were developed in collaboration with the International Aluminium Institute to analyse potential future alternatives. The four scenarios are based on a combination of two possible future alternatives for primary aluminium production and two possible future alternatives for product fabrication, highlighted in table 5. Any number of additional scenarios can be incorporated into the model in order to assess their impact on the future aluminium cycle; however, only these four scenarios were analysed since this paper aims to highlight the use of a stock-driven model for scenario analysis and strategy development.

Table 5. Four Scenarios for Meeting Future Aluminium Demand

Primary AL Scenarios	Product Fab Scenarios	Combined Scenarios
Middle East dominates primary AL production	Fabrication follows domestic demand	Middle East dominates primary AL production, Fabrication follows domestic demand
	Fabrication integrated with primary AL production	Middle East dominates primary AL production, Fabrication integrated with primary AL production
China dominates primary AL production	Fabrication follows domestic demand	China dominates primary AL production, Fabrication follows domestic demand
	Fabrication integrated with primary AL production	China dominates primary AL production, Fabrication integrated with primary AL production

2.2.2.1. Primary Aluminium Production Scenarios

The primary aluminium scenarios assumed that either the Middle East or China dominate primary AL production from 2012 to 2050, such that there is no build-up of primary aluminium production capacity in any region except the dominant region. Thus, no additional primary aluminium smelters or expansions of existing smelters were assumed to be built in any of the non-dominant regions and any existing smelters were assumed to reach their end of life. Primary aluminium production was then assumed to follow the declining primary aluminium smelter capacity in non-dominant regions, while the dominant region would produce any remaining primary aluminium required by the global market.

To create these scenarios, smelter capacity for all primary aluminium smelters within each region from 1900 to 2013 was analysed using sources from GeniSim (2014), Light Metal Age (Pawlek, 2012), and the UN Conference on Trade and Development (UNCTAD, 2000). Here, 2013 was selected as the cut-off point, since any plans for additional smelters, expansions of existing smelters, or smelter closures between 2011 and 2014 should be accounted for. The compiled data was separated into inflows of primary aluminium smelter

capacity from the construction of new smelters or the expansion of existing smelters, as well as outflows of primary aluminium smelter capacity from the closure of smelters or production lines. This data was then aggregated to total primary aluminium capacity inflows and outflows for each region based on the location of the smelters. In addition, the age of the primary aluminium smelters within each region was calculated. An approach similar to the one taken to forecast in-use stock dynamics was applied, illustrated in table 6.

Table 6. Primary Aluminium Production Capacity Approach for Non-Dominant Regions

	Capacity Inflows	Capacity Outflows	Capacity Change	Capacity Stock
Historical Data (1900-2013)			1	1
Forecasted Data (2014-2050)	2	3	4	4

1. Using the aggregated data of historical capacity inflows and capacity outflows of primary aluminium smelters from 1900 to 2013, a capacity change and capacity stock were calculated for each of the non-dominant regions
2. For the non-dominant regions future capacity inflows were set to zero for all future years from 2014 to 2050, since the scenarios assumed that no additional capacity would be built-up in the non-dominant regions
3. Capacity outflows for each of the non-dominant regions were calculated using the same methodology used in the in-use stock calculations illustrated in equation 3. Future outflows were based on historical inflows using average lifetime and standard deviations of the primary aluminium smelters in each region, shown in table 7, based on the age distribution of the smelters. Due to lack of sufficient data to calculate average lifetime and standard deviation for Africa, and lack of sufficient data to calculate standard deviation for Middle East and Rest of Asia, data from Latin America was used as a proxy. This was because Latin America was assumed to have the most similar smelter characteristics in terms of age and technology.

Table 7. Average Lifetimes and Standard Deviations of Primary Aluminium Smelters

Region	Average Lifetime	Standard Deviation
Europe	54	26
North America	58	20
Latin America & Caribbean	39	17
Africa	39	17
Middle East	38	17
China	9	6
India	48	19
Rest of Asia	25	17
Australia & Oceania	47	6
USSR	55	19

4. Using the future capacity inflows and future capacity outflows, capacity stock change and capacity stock were calculated for future years from 2014 to 2050 for the non-dominant regions. The yearly change in smelter capacity stock from 2011 to 2050 was also calculated.

Since it was assumed that future primary aluminium production for the non-dominant regions would follow smelter capacity stock, the yearly change in primary aluminium smelter capacity stock from 2011 to 2050 was applied to forecast future primary aluminium production from 2012 to 2050 for the non-dominant regions. This is shown in equation 6 below.

Equation 6. Non-Dominant Region Primary Aluminium Production Calculation

$$NDomPALP_t = NDomPALP_{t-1} * \%CapChng_{t,t-1}$$

where $NDomPALP_t$ is the primary aluminium produced in non-dominant regions in year t , $\%CapChng_{t,t-1}$ is percent change in smelter capacity stock in the non-dominant region from year $t-1$ to year t , for years 2012 to 2050

As mentioned earlier, the dominant region, which is the Middle East or China depending on the scenario, would then produce any remaining primary aluminium demanded by the global market. Equation 7 shows the exact methodology used to calculate the dominant region's primary aluminium production.

Equation 7. Dominant Region Primary Aluminium Production Calculation

$$DomPALP_t = GDAL_t - GSecAL_t - \sum NDomPALP_t$$

where $DomPALP_t$ is the primary aluminium produced in the dominant region,
 $GDAL_t$ is the global demand for aluminium ingot,
 $GSecAL_t$ is the level of secondary aluminium available globally,
 $\sum NDomPALP_t$ is the total primary aluminium produced in all non-dominant regions,
in year t from 2012 to 2050

Through this approach, the stock-driven, trade-linked, multi-regional model is able to analyse future primary aluminium production flows within each of the 10 regions in a situation where the Middle East would dominate primary aluminium production, or an alternative situation where China would dominate primary aluminium production. These assumptions can be reviewed under the “PrimAL” and “PrimALCap” tabs in the model’s Excel file.

2.2.2.2. Product Fabrication Scenarios

The first product fabrication scenario assumed that the fabrication of aluminium containing products entirely supplies the region’s domestic demand in each of the 11 product categories by 2050. This makes product fabrication more localized and each region more self-sufficient in meeting demand for aluminium products.

Table 8. Product Fabrication Domestic Demand Scenario Approach

Region	2011	2012 - 2049	2050
Europe	% distribution of product fabrication for each of 11 product categories	Negative Square Growth Formula used to calculate % distribution	% distribution of net shipments for each of 11 product categories
North America			
Latin America & Caribbean			
Africa			
Middle East			
China			
India			
Rest of Asia			
Australia & Oceania			
USSR			

Table 8 illustrates the methodology used to create this first scenario for each of the 11 product categories. The historical product fabrication level in 2011 was broken down into a percentage distribution between the 10 different regions. Next, the forecasted shipments in 2050 were also broken down into a percentage distribution between the 10 different regions. For the years 2012 to 2049, the same negative growth formula used in forecasting in-use

stock per capita was used to calculate the percent distribution between the 10 regions over time, illustrated in equation 8.

Equation 8. 2012-2049 Distribution by Region Product Fabrication Negative Square Growth Formula

$$\%Dist_{p,r,t} = \frac{(\%Dist_{p,r,2050} - \%Dist_{p,r,2011}) * (t - 2050)^2}{-(2050 - 2011)^2} + \%Dist_{p,r,2011}$$

where $\%Dist_{p,r,t}$ is the percent regional distribution of global product fabrication of product category p , for region r , at time t from 2012 to 2049

Once the regional distribution was calculated, the global demand in terms of shipments for each of the 11 product categories was multiplied by the distribution to find the product fabrication level within each of the 10 regions for each of the product categories. Equation 9 shows the exact formula used.

Equation 9. Product Fabrication Calculation

$$PFab_{p,r,t} = PS_{p,t} * \%Dist_{p,r,t}$$

where $PFab_{p,r,t}$ is the level of product fabrication,
 $PS_{p,t}$ is the level of global demand for product shipments,
 $\%Dist_{p,r,t}$ is the percent regional distribution
of product category p , for region r , at time t from 2012 to 2050

The second product fabrication scenario assumed that the fabrication of aluminium containing products is integrated with primary aluminium production. This assumption supposes that future product fabrication for each of the 11 different product categories within each region follows the same growth rate as future primary aluminium production from 2012 to 2050.

Table 9. Product Fabrication Integrated with Primary Scenario Approach

Region	2011	2012 - 2050
Europe	% distribution of product fabrication for each of 11 product categories	Percent change in primary aluminium production (NDomPALP and DomPALP) used to calculate % distribution
North America		
Latin America & Caribbean		
Africa		
Middle East		
China		
India		
Rest of Asia		
Australia & Oceania		
USSR		

Table 9 illustrates the methodology used to create this second scenario for each of the 11 product categories. As before, historical product fabrication level in 2011 was broken down into a percentage distribution between the 10 different regions. Next, the yearly percent change in *NDomPALP* or *DomPALP* depending on whether the region was dominant or not, was calculated for each of the regions. This yearly change was then applied to calculate each region's distribution of product fabrication from 2012 to 2050 for each of the 11 product categories, as illustrated in equation 10.

Equation 10. 2012-2050 Distribution by Region Product Fabrication Integrated with Primary

$$\%Dist_{p,r,t} = \%Dist_{p,r,t-1} * \%ChngPALP_{r,t}$$

*where %ChngPALP_{r,t} is the percent change in primary aluminium production,
%Dist_{p,r,t} is the percent regional distribution of global product fabrication
of product category p, for region r, at time t from 2012 to 2050*

As with the first product fabrication scenario, once the regional distribution was calculated, the global demand in terms of product shipments for each of the 11 product categories was multiplied by the distribution to find the product fabrication level within each of the 10 regions for each of the product categories. Equation 9 shows the exact formula used.

Thus, the model is able to analyse two potential future alternatives for how product fabrication for the 11 product categories within the 10 regions could evolve in the future. As mentioned before, additional scenarios for how the product fabrication is distributed across the various regions could be incorporated into the model; however, these were not explored to maintain simplicity. These assumptions can be reviewed under the “ProdFab_DD” and “ProdFab_INT” tabs in the stock-driven model’s Excel file.

2.2.2.3. Bauxite, Alumina, and Scrap Scenario Projections

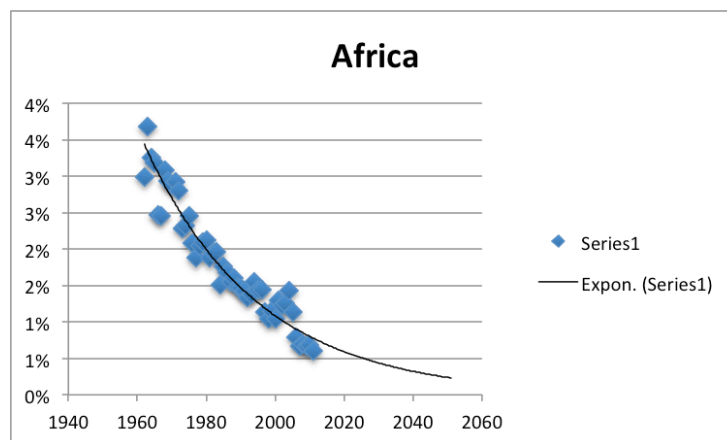
In addition to developing scenarios to forecast primary aluminium production and product fabrication, the other parts of the aluminium cycle – bauxite production, alumina production, and scrap treatment – also need to be forecasted to meet the level of aluminium demand. Similar to the in-use stock scenario projections, only one scenario was developed for bauxite production, alumina production, old scrap treatment, and new scrap treatment. While the stock-driven model can incorporate additional scenarios, these were not explored in order to maintain simplicity in the model.

Table 10. Bauxite, Alumina, Scrap Scenario Approach

Region	1962 - 2011	2012 - 2049	2050
Europe	% distribution of bauxite production, alumina production, old scrap and new scrap treatment	Negative Square Growth Formula used to calculate % distribution	Forecasted distribution based on Excel trendlines, normalized to 100%
North America			
Latin America & Caribbean			
Africa			
Middle East			
China			
India			
Rest of Asia			
Australia & Oceania			
USSR			

The approach for developing the scenario projections for bauxite production, alumina production, old scrap treatment, and new scrap treatment are the same and is illustrated in table 10. First, the % distribution of bauxite production, alumina production, and old and new scrap treatment was calculated from 1962 to 2011 using historical data from the historical models (Ramkumar, 2013). This data was plotted in Excel and similar to in-use stock per capita, Excel trendlines were used as a guide to understand the magnitude of the percent distribution of production in each region in 2050. Figure 7 shows an example of how the trendlines were used to understand the percent distribution of global alumina production in Africa in 2050. These forecasts were developed for each of the 10 regions for bauxite production, alumina production, old scrap treatment, and new scrap treatment. The forecasts were then adjusted and normalized such that the sum of the percent distribution across the 10 regions equalled 100%.

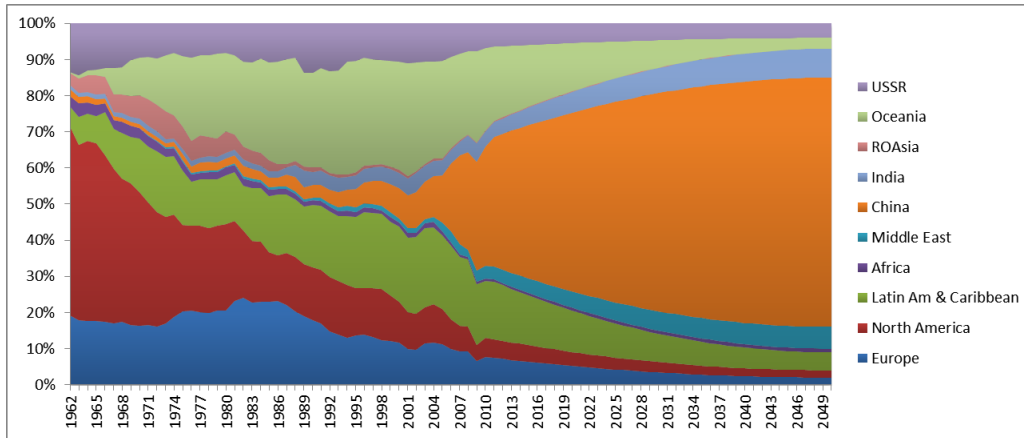
Figure 7. 2050 Forecasted Distribution for Alumina Production in Africa



Next, the percent distribution of production in each region between 2012 and 2049 was calculated using the same negative square growth function using the historical 2011 data and

the forecasted 2050 data, illustrated in equation 8. Figure 8 shows an example of the historical and forecasted regional distribution of alumina production based on this approach.

Figure 8. Regional Distribution of Alumina Production 1962-2050



These forecasted regional distributions were then multiplied by the global demand for bauxite, the global demand for alumina, the global market supply of old scrap, and the global market supply of new scrap respectively. Doing so provides the level of bauxite production, alumina production, old scrap treatment, and new scrap treatment within region, as shown in equations 11-14.

Equation 11. Bauxite Production Calculation

$$BProd_{r,t} = GDBaux_t * \%DistBaux_{r,t}$$

where $BProd_{r,t}$ is the level of bauxite production,
 $GDBaux_t$ is the level of global demand for bauxite,
 $\%DistBaux_{r,t}$ is the percent regional distribution of bauxite production for region r ,
at time t from 2012 to 2050

Equation 12. Alumina Production Calculation

$$AProd_{r,t} = GDAlum_t * \%DistAlum_{r,t}$$

where $AProd_{r,t}$ is the level of alumina production,
 $GDAlum_t$ is the level of global demand for bauxite,
 $\%DistAlum_{r,t}$ is the percent regional distribution of alumina production for region r ,
at time t from 2012 to 2050

Equation 13. Old Scrap Treatment Calculation

$$OScrapTreat_{r,t} = GMOScrap_t * \%DistOScrap_{r,t}$$

where $OScrapTreat_{r,t}$ is the level of old scrap treatment,
 $GMOScrap_t$ is the level of global market supply of old scrap,
 $\%DistOScrap_{r,t}$ is the percent regional distribution of old scrap treatment for region r ,
at time t , from 2012 to 2050

Equation 14. New Scrap Treatment Calculation

$$NScrapTreat_{r,t} = GMNScrap_t * \%DistNScrap_{r,t}$$

*where NScrapTreat_{r,t} is the level of new scrap treatment,
GMNScrap_t is the level of global market supply of new scrap,
%DistNScrap_{r,t} is the percent regional distribution of new scrap treatment for region r,
at time t, from 2012 to 2050*

From this approach, the model is able to evaluate the future flows from 2012 to 2050 for the remainder of the aluminium cycle involving bauxite, alumina, and scrap treatment based on the level of aluminium demand determined in the in-use stock scenario projections. This is only one of the many possible scenarios for how the rest of the aluminium cycle can evolve in the future, and the model is able to incorporate and adapt additional scenarios for future flows.

By evaluating the above scenarios, the model can answer the second strategic question, “How can future production of aluminium and fabrication of final products meet this demand?” The approaches taken above enables the stock-driven model to evaluate various future alternatives for primary aluminium production and product fabrication, as well as scenarios for upstream processes such as bauxite production and alumina production and downstream processes such as scrap treatment. These assumptions can be reviewed under the “Bauxite,” “Alumina,” and “ScrapOld” and “ScrapNew” tabs, as well as the “Scenarios and Inputs” tab in the model’s Excel file.

2.2.3. Additional Model Assumptions

Aside from the scenarios, the stock-driven, trade-linked, multi-regional model utilizes a variety of other assumptions for parameters such as utilization rates, collection rates, loss rates, etc. to determine the flows described as Calculated Data flows and highlighted in grey in figure 1. Some of these parameter assumptions were sourced directly from industry, while other parameter assumptions were sourced from the historical data.

Table 11. Calculated Data Parameters Industry Assumptions

Calculated Data Flow	Parameter Description	Source
AB,0. Beneficiation Loss	Percent of produced bauxite lost in mining process due to beneficiation	Rio Tinto & Geoscience Canada
A4,32. Dross Loss	Percent of primary aluminium that is unrecovered dross	International Aluminium Institute
A29,32. Collection & Under Investigation Loss	Old Scrap by product category, New Scrap, and Internal Scrap Collection Rates	International Aluminium Institute
A31,32. Treatment Loss	Loss of Old, New, and Internal Scrap from treatment	International Aluminium Institute

Table 11 provides an overview of all the flows that are based directly from industry assumptions and the source of the data. For most of the calculated data flows in table 11, the assumptions from the industry were the same assumptions used to calculate the historical data. The “A29,32. Collection & Under Investigation Loss” parameter assumptions for old scrap collection rates varied by year from 1962 to 2011 across the different product categories, so the most recent 2011 parameter assumptions from the International Aluminium Institute were used to calculate the future flows from 2012 to 2050.

Table 12. Calculated Data Parameters Historical Average

Calculated Data Flow	Parameter Description	Source
A2,0. Refining Losses and Other Uses	Ratio of losses from alumina refining and other uses for alumina compared to alumina production	Historical Average from 2000 to 2011
A4,0. Smelting Losses and Other Uses	Ratio of losses from aluminium smelting and other uses for aluminium compared to primary aluminium production	Historical Average from 2000 to 2011
A6a,29. Internal Scrap Generation	Percent of total final product fabrication that is lost as internal scrap	Historical Average from 2000 to 2011
A6b,29. New Scrap Generation	Percent of total final product fabrication that is lost as new scrap	Historical Average from 2000 to 2011
A6,0. Destr Uses and Semi-Trade	Ratio of aluminium for destructive uses and regional trade of semi-fabrication compared to total final product fabrication	Historical Average from 2000 to 2011

Some of the other flows were based on historical data, as shown in table 12. For these flows, the parameter assumptions were taken as an average of historical data from the years 2000 to 2011 (Ramkumar, 2013). The historical data itself is based on industry assumptions or the Mass Balance principle; however, since the stock driven model simplified and aggregated these particular flows the industry assumptions were no longer directly applicable. The years 2000 to 2011 were selected to utilize data from the most recent decade for the parameter assumptions for future flows. These assumptions can be reviewed under the “Scenarios and Inputs” tab in the model’s Excel file.

All remaining flows shown in figure 1 in blue utilized the Mass Balance principle, described in equation 5, and shown in a more general form in equation 15 below. This was done to ensure that all flows were accounted for and that the model maintains mass balance consistency that does not violate the principles of conservation of mass.

Equation 15. General Form of Mass Balance Principle

$$I_t = O_t + \Delta S_t$$

where I_t is the input into a process, O_t is the outflow from a process, ΔS_t is the stock change within the process, for year t from 2012 to 2050

The stock-driven model also incorporates new assumptions for the bauxite resources process, “B. Bauxite Resources and Mining” in figure 1. In the historical models (Ramkumar, 2013), the bauxite resources were calculated using reserves data from the US Geological Survey. However, in the stock-driven models, Bauxite Reserve Base data from the USGS (2009) was used instead. The reason for this shift is because the reserve base is defined as “parts of a resource that have a reasonable potential for becoming economically viable” and “includes those resources that are currently economic (reserves), marginally economic (marginal reserves), and some of those that are currently subeconomic (subeconomic resources)” (USGS, 2009). This provides a better understanding of the availability of bauxite in the future, since bauxite resources that are marginally economic and subeconomic may prove to be economically viable in the future and available for mining and extraction. The reason this process exists is to help understand the level of bauxite demanded due to the various scenarios and whether production levels will require a higher level of bauxite resources relative to what is currently known to be available.

As was the case with the historical models (Ramkumar, 2013), the stock-driven models also incorporate a process called “32. System Losses,” shown in figure 1. This process captures the magnitude of losses of aluminium in the smelting, manufacturing, scrap collection, and treatment processes. As it is a stock accumulation process, it represents the opportunity present in improving the processes in the global aluminium cycle to reduce losses from aluminium production as well as scrap recovery and treatment.

3. Results and Interpretation

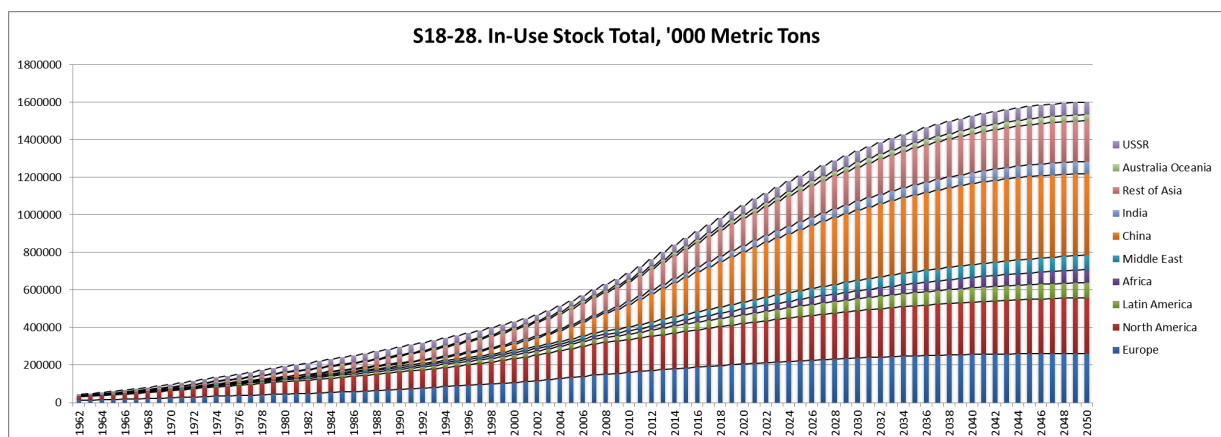
With all the methodology established in the previous section, the stock-driven, trade-linked, multi-regional model is able to provide a comprehensive view of the future global

aluminium cycle. This section provides insights into how future flows will evolve from 2012 to 2050 across the 10 regions based on the specific scenarios, assumptions, and calculations outlined in the previous section. Here the paper will showcase how the stock-driven model is able to evaluate various alternatives for future aluminium flows in the different regions to answer key questions relevant to the industry and provide insights for strategy development. These charts can also be viewed in the tab “Time Series Charts” in the stock-driven model’s Excel file.

3.1. Future Demand for Aluminium Products and Future Availability of Scrap

The first part of the answer to the first strategic question “What is the future demand for aluminium products and the future availability of scrap given the stock dynamics of aluminium consumption in different regions within the different final product categories?” is shown in figure 9. The figure shows the in-use stock of aluminium for all 11 product categories in total broken down by the 10 regions from 1962 to 2011, describing the future per capita consumption of aluminium globally.

Figure 9. Total In-Use Stock of Aluminium for All Product Categories by Region from 1962-2050



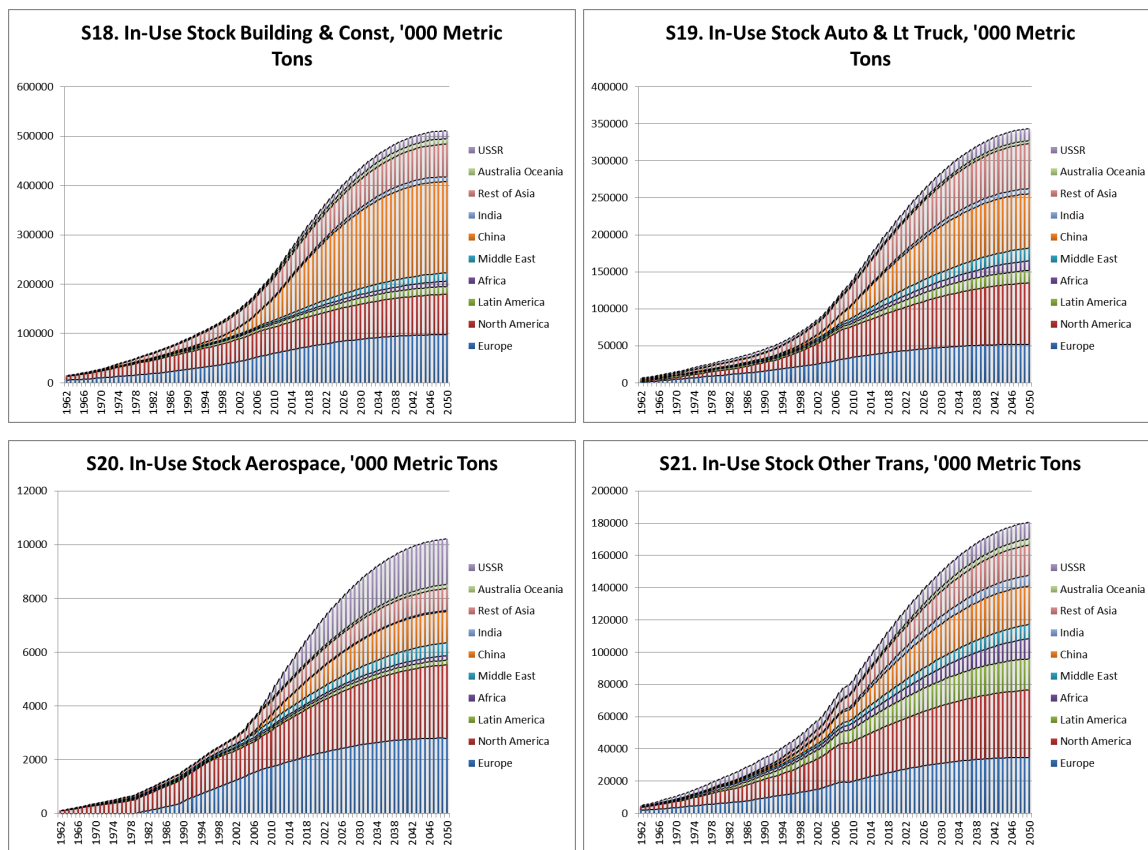
Based on the assumptions and the scenarios described in section 2.2.1, the future consumption of aluminium in 2050 is expected to be roughly 2 times 2011 levels, in large part due to increases in future consumption in China and Rest of Asia. China is expected to become the largest consumer of aluminium, exceeding levels in Europe and North America. Rest of Asia is also expected to reach aluminium consumption levels at par with North America and Europe.

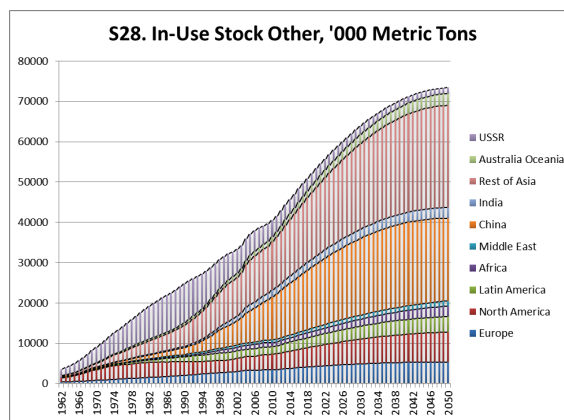
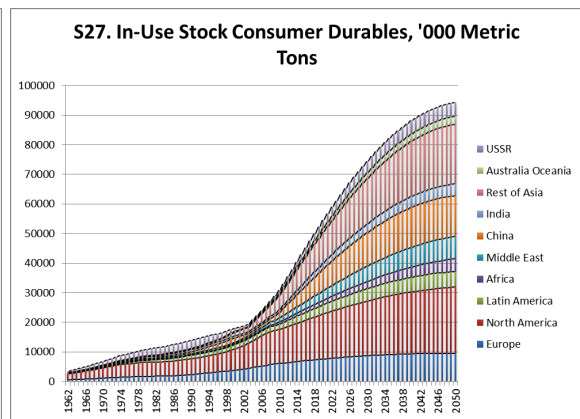
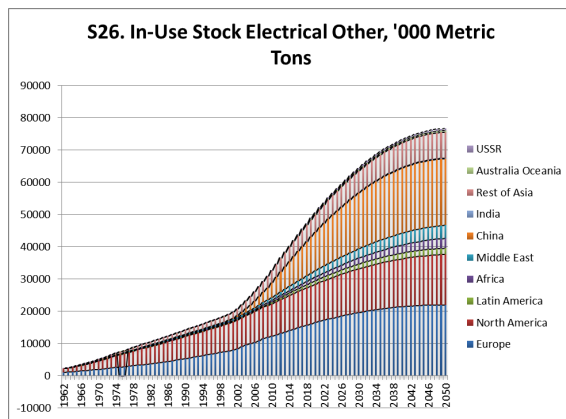
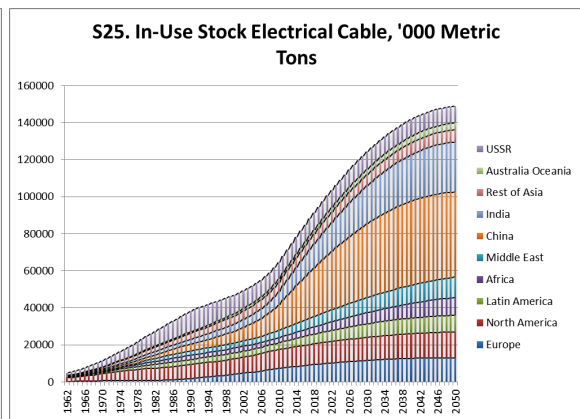
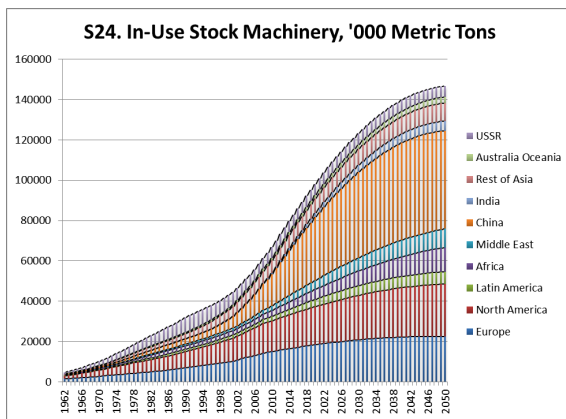
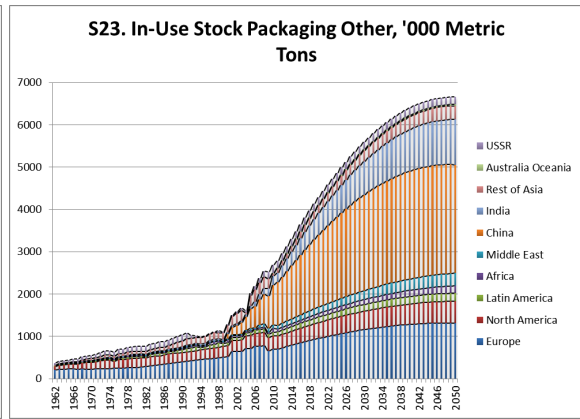
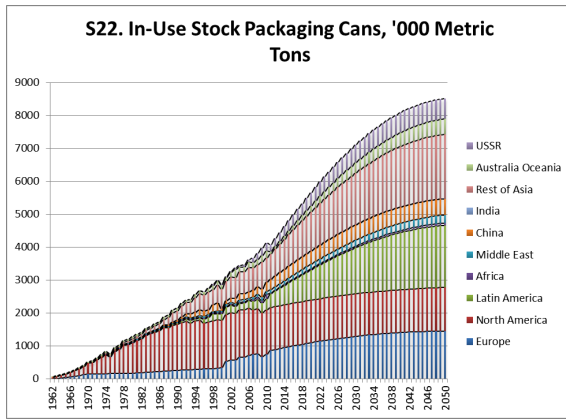
Comparing these results to the study by the USGS, which mentioned that the level of aluminium consumption in 2025 is 2.5 times compared to 2006 levels (Menzie, 2010), the

stock-driven model results show that the level of aluminium consumption in 2025 is about 2 times compared to 2006 levels. This comparison, along with the model results for in-use stock of aluminium per capita compared to 9 different scenarios in figure 5 (Liu, Bangs, & Mueller, 2013), reinforces that the stock-driven model takes a more conservative approach in estimating future aluminium consumption.

The model is able to further disaggregate the future consumption of aluminium into the various product categories, as shown in figure 10. These results provide insights into which of the product categories are expected show the greatest changes in aluminium consumption in the future, as well as which regions are expected to see the greatest level of consumption for each product category.

Figure 10. In-Use Stock of Aluminium by Product Category by Region from 1962-2050



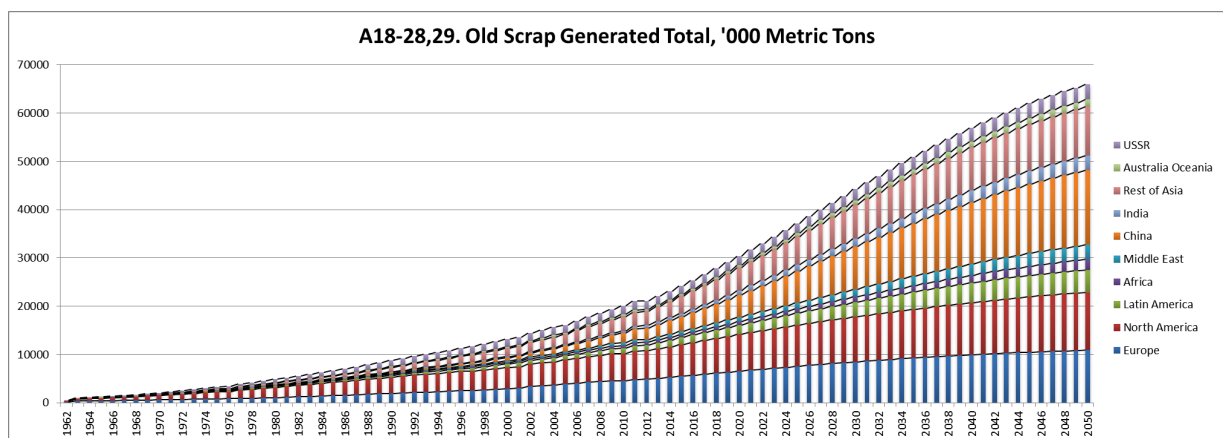


Given the assumptions made, all 11 product categories show significant increases in aluminium consumption by 2050. The majority of the product categories' increase in

consumption is due to China; however, for certain categories like Packaging Cans, Consumer Durables, and Other, Rest of Asia also has a large contribution to the increased consumption. Looking in greater detail, Buildings and Construction shows the greatest absolute increase in aluminium consumption of nearly 300 million metric tons from 2011 to 2050, mainly due to significant increases in China. Auto and Light Truck makes up the second biggest product category for aluminium consumption by 2050, with nearly 400 million metric tons of in-use stock; the increase comes mostly due to increases in China and Rest of Asia, as well as North America. Other Transportation also shows large growth in aluminium consumption of nearly 100 million metric tons by 2050 due to increases across all regions.

The second part of the answer to the first strategic question shows the consequences of this increased aluminium consumption in the future. Figure 11 shows the total amount of old scrap generated for all the product categories broken down by region from 1962 to 2050. The old scrap generated shows the level of aluminium that flows out from society after consumption as products reach their end of life and become obsolete, and partly helps answer the question of future scrap availability given the stock dynamics of aluminium consumption.

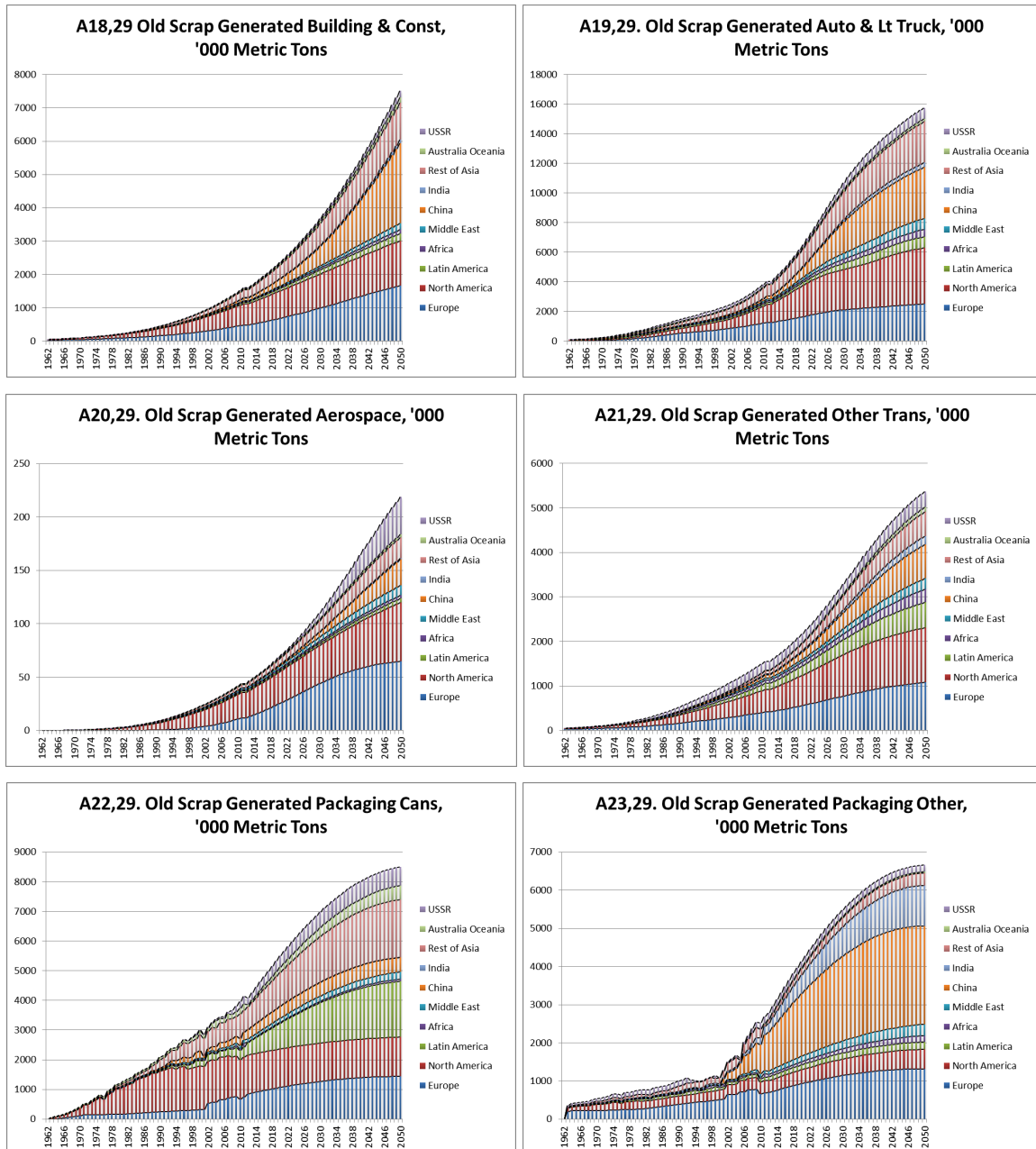
Figure 11. Total Old Aluminium Scrap Generated for All Product Categories by Region from 1962-2050

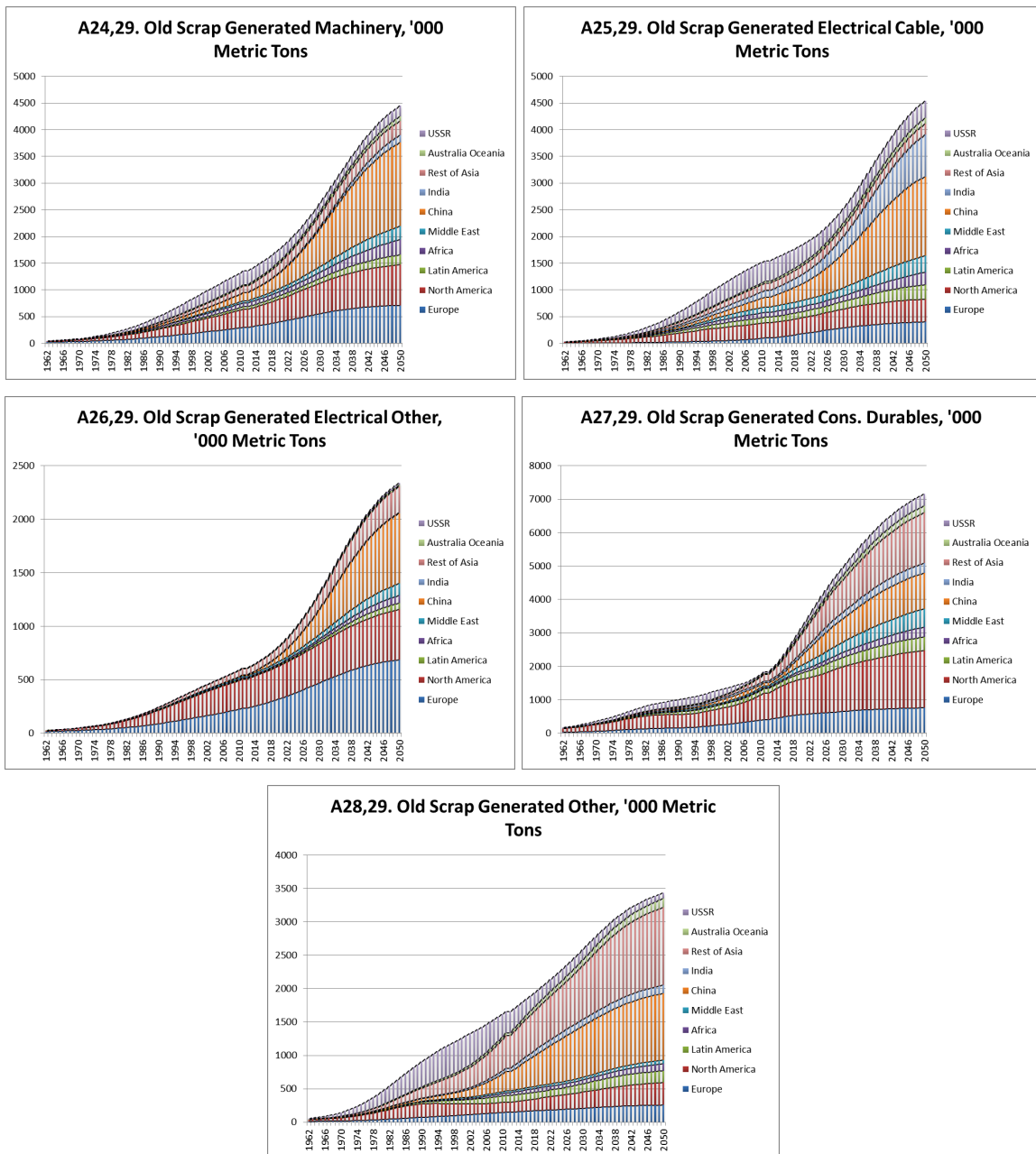


From the assumptions related to the dynamics of in-use stock and the lifetimes of the various product categories, the level of old scrap available for recycling and reuse in 2050 is expected to be nearly 3 times 2011 levels, as seen in figure 11. China, North America, Europe, and Rest of Asia are the regions with the biggest availability of old scrap, with the largest growth of scrap generation occurring in China and Rest of Asia. This can be explained by the large build-up of in-use stock of aluminium in China and Rest of Asia, as well as the steady increase in in-use stock in North America and Europe, shown in figure 9.

Delving deeper into the various product categories, there are close parallels between the in-use stock of aluminium charts in figure 10 and the old scrap generated charts, shown in figure 12.

Figure 12. Old Aluminium Scrap Generated by Product Category by Region from 1962-2050



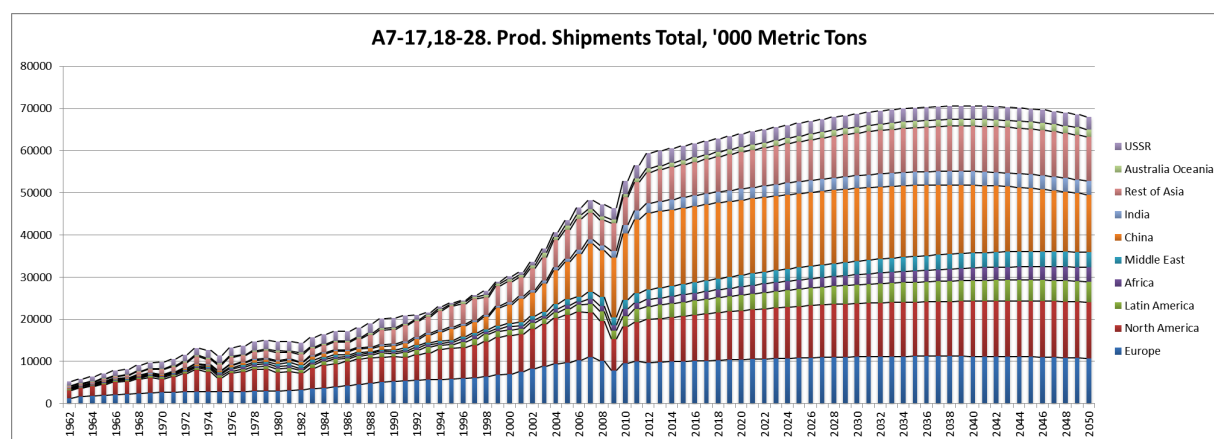


The model shows how the availability of old scrap within the 11 product categories for the 10 different regions is heavily influenced by the level of aluminium consumption, but also the lifetimes of the different products. The regions that have the largest availability of old scrap in each of the product categories, China in the majority of cases, are the very regions that have a high build-up of in-use stock of aluminium. However, lifetimes play a significant role in determining which of the product categories are the biggest sources of old scrap. Auto and Light Truck, which has the second biggest level of aluminium consumption in 2050, has the biggest level of old scrap generated, nearly 16 million metric tons by 2050, owing to its relatively shorter lifetime. Though Building and Construction is still a significant source of old scrap, it is not the largest because of its assumed lifetime of 50 years, causing aluminium

in buildings to stay in-use for a longer period of time. As mentioned before in section 2.2, the fixed lifetime assumptions used are highly uncertain and may change over time, thus impacting the results shown above.

The last part of the answer to the first strategic question shows the demand for aluminium products in the future given the levels of aluminium consumption shown in figures 9 and 10, as well as the level of aluminium outflows shown in figures 11 and 12. Figure 13 shows the total shipments for aluminium products from 1962 to 2050, and highlights the expected future demand for aluminium across all 11 product categories within each of the 10 regions.

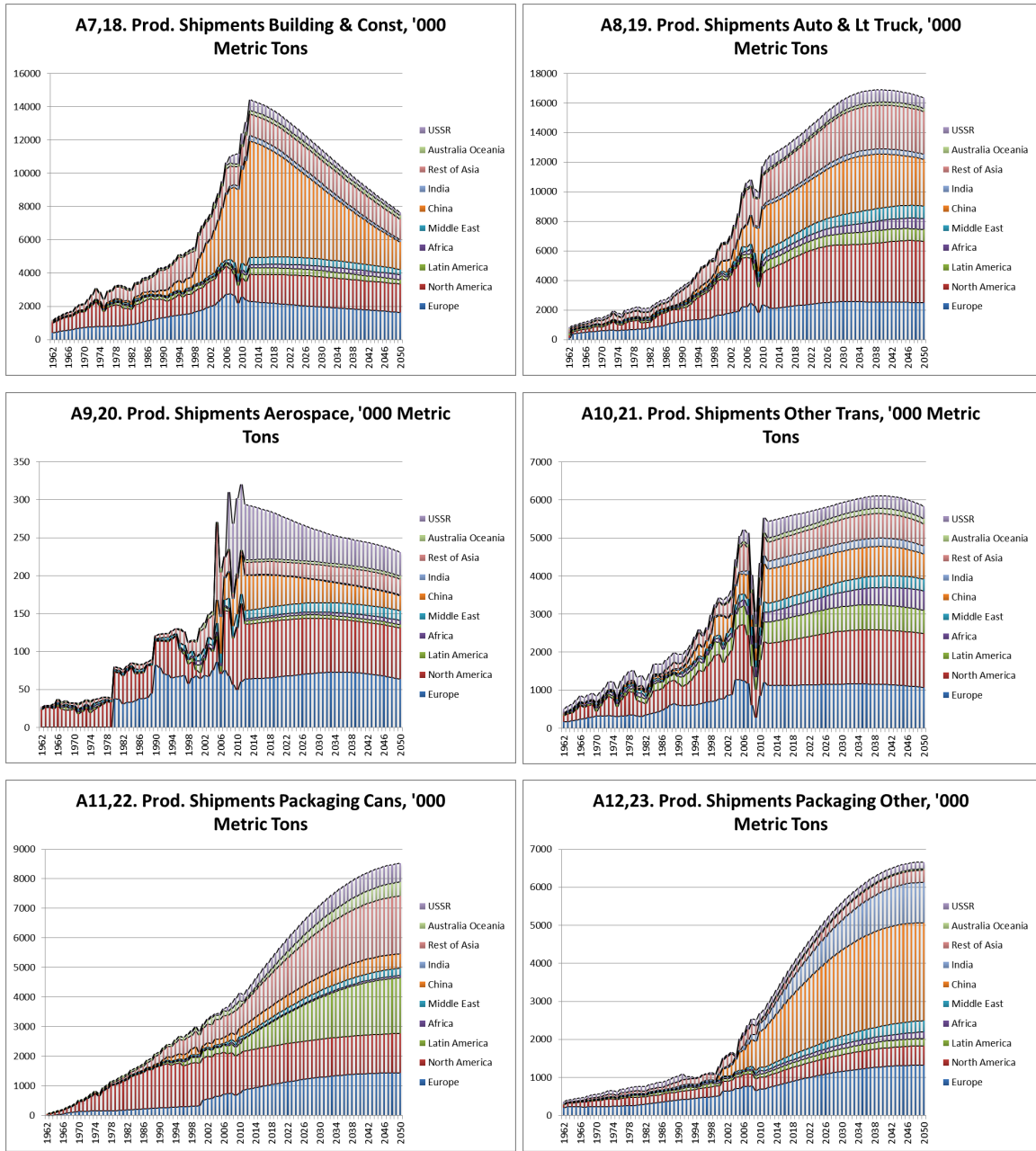
Figure 13. Total Product Shipments for All Product Categories by Region from 1962-2050

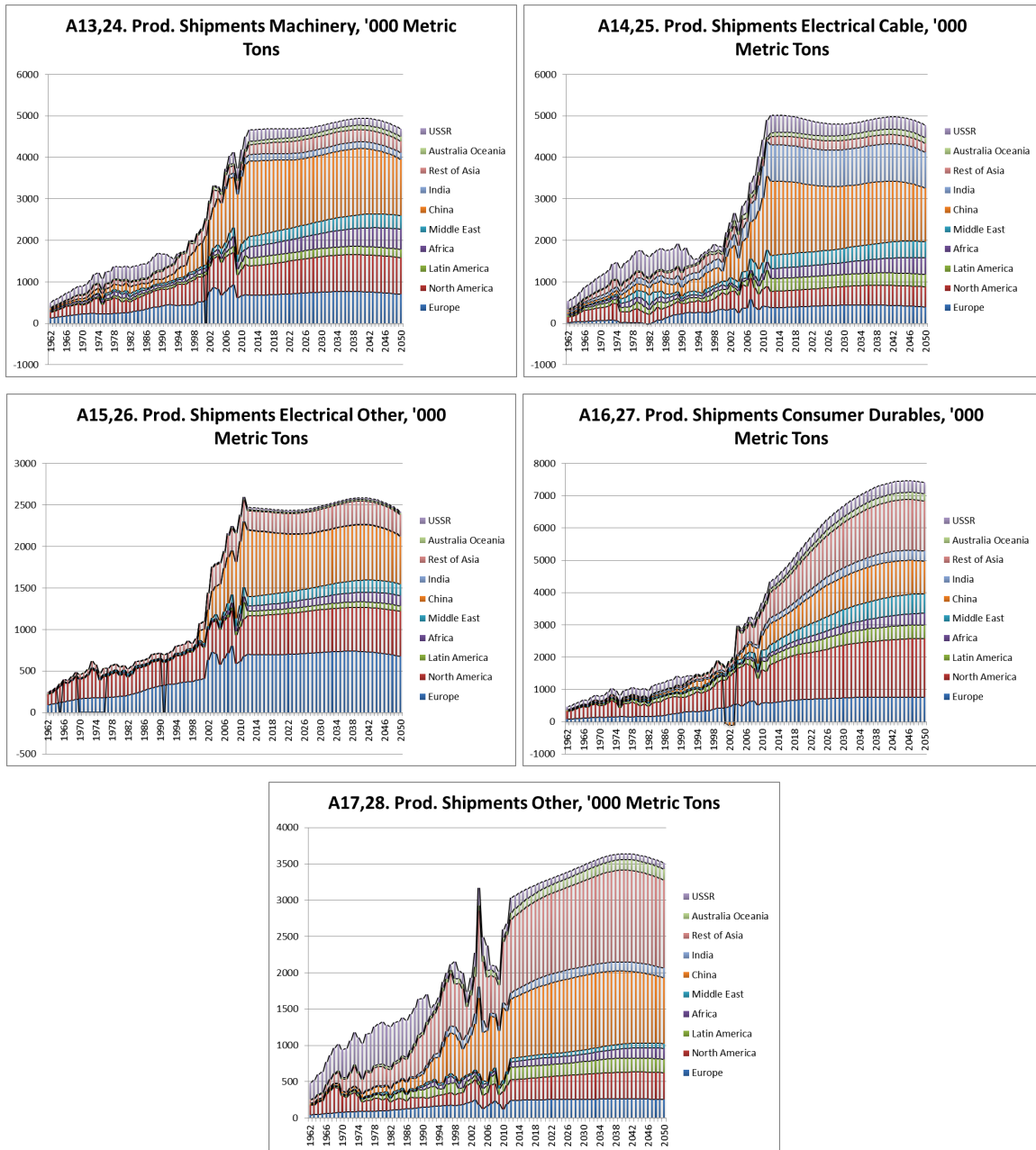


As figure 13 shows, from the assumptions made about the stock dynamics, consumption forecasts, and lifetimes of aluminium products, future demand for aluminium products is expected to increase gradually from 2011 to around 2040, where it reaches a peak of around 70 million metric tons, and then decline from 2040 to 2050. The gradual increase and subsequent decline in future aluminium demand can be attributed to the fact that the future aluminium consumption levels assumed in the model are very conservative, as was shown in figure 5, and tend to reach a saturation point by 2050. Moreover, the lifetimes for some of the largest aluminium consuming product categories are quite long. As result, there is enough aluminium in-use to meet consumption needs by 2050, so future demand for aluminium products tends to stabilize and then slightly decline.

Further disaggregation into product categories provide more detailed insight into the future demand for different types of aluminium products. Figure 14 shows the future aluminium demand for the 11 product categories.

Figure 14. Product Shipments by Product Category by Region from 1962-2050





From figure 14, the results show that for product categories with the smallest lifetimes, such as Packaging Cans and Packaging Other, there is a significant growth in aluminium demand of nearly 4 million metric tons between 2011 and 2050 to meet future aluminium consumption needs. This is also the case for Consumer Durables and Auto and Light Truck, which have smaller lifetimes of 12 to 20 years. There is a large growth in product shipments demanded of around 3 million to 4 million metric tons between 2011 and 2050 to meet future aluminium consumption levels. However, for the remaining categories which have lifetimes of 30 to 50 years, there is a stable or declining level of future aluminium demand, due to the longer presence of these products in-use. This is particularly true for the Building and Construction product category, which sees a sharp decline in demand for aluminium until

2050. The main factor contributing to this decline is the significant build-up of in-use stock of aluminium in buildings in China, which due to its long lifetime, reduces future demand and thus future shipments. As mentioned before, these results are entirely dependent on the lifetime assumptions made in section 2.2.

Within each of the product categories, the regions that have the largest aluminium consumption levels, as shown in figure 10, are also the very same regions that have the largest future demand for aluminium. For the majority of the product categories, China is the main region with significant aluminium demand to 2050. However, Rest of Asia is also a key growth market for aluminium products, particularly in Auto & Light Truck, Packaging Cans, Consumer Durables, and Other. The regions with strong historical demand for aluminium products, North America and Europe, continue to be key regions with significant levels of future demand for many product categories.

Thus, the stock-driven, trade-linked, multi-regional model is able to answer the first strategic question, “What is the future demand for aluminium products and the future availability of scrap given the stock dynamics of aluminium consumption in different regions within the different final product categories?” By making a series of assumptions and evaluating specific scenarios for how aluminium in-use stock could evolve in the future, the stock-driven model is able to evaluate future aluminium consumption and its impacts on scrap availability and aluminium demand.

3.2. Future Production to Satisfy Future Demand

With the future demand for aluminium products and the future availability of scrap understood, the second strategic question “How can future production of aluminium and fabrication of final products meet this demand?” can be answered by analysing the 4 different scenarios for future production of aluminium and fabrication of final products, outlined in section 2.2.2. The following section will review each of the scenarios separately to highlight how the model is able to evaluate the impact of varying assumptions on the future flows of the global aluminium cycle.

In evaluating the results of the scenarios, product fabrication will first be discussed. Next, the total amount of old, new, and internal scrap collected will be analysed, since the volume of new and internal scrap generated is dependent on the product fabrication scenario. The volume of scrap impacts the amount of primary aluminium needed vs. recycled scrap used. This will then lead to understanding the production of primary aluminium based on the

scenario selected. Lastly, the effects of primary aluminium production on alumina and bauxite will be analysed.

3.2.1. Scenario 1: Middle East dominates primary AL production, Fabrication follows domestic demand

The first scenario for future aluminium production and final product fabrication assumes that by 2050 future primary aluminium production is dominated by the Middle East and by 2050 fabrication of final products containing aluminium is satisfied by domestic facilities that meet domestic demand. Figure 15 shows the product fabrication of all the product categories by region – the global total is the same as the aluminium demand in figure 13, since the model assumes that all demand is met. However, because the product fabrication scenario assumes that domestic demand within each region is met domestically by 2050, the regional breakdown of product fabrication between the 10 regions is very similar to figure 13. Even after disaggregating product fabrication by product category, as shown in figure 16, the results remain quite similar to the aluminium demand for each product category shown in figure 14.

Figure 15. Scenario 1: Total Product Fabrication for All Product Categories by Region from 1962-2050

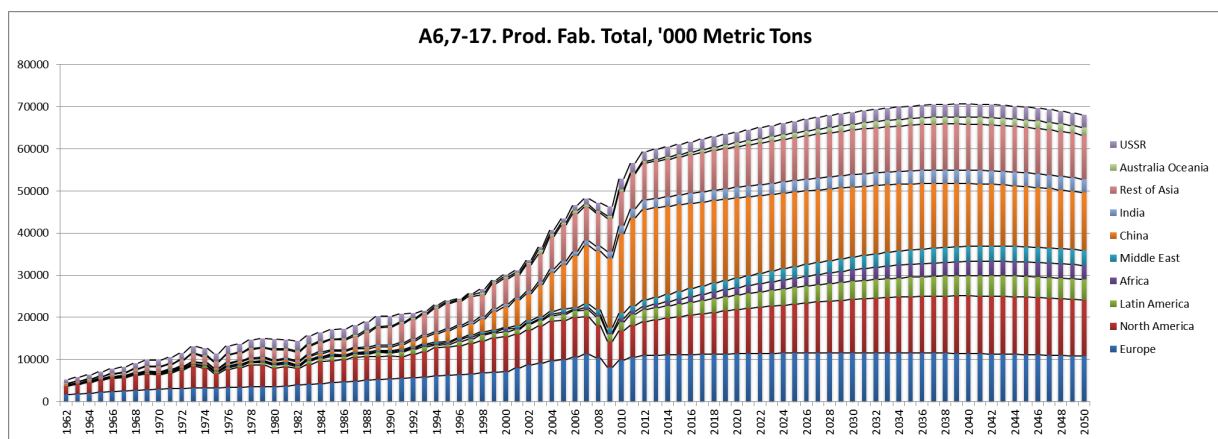
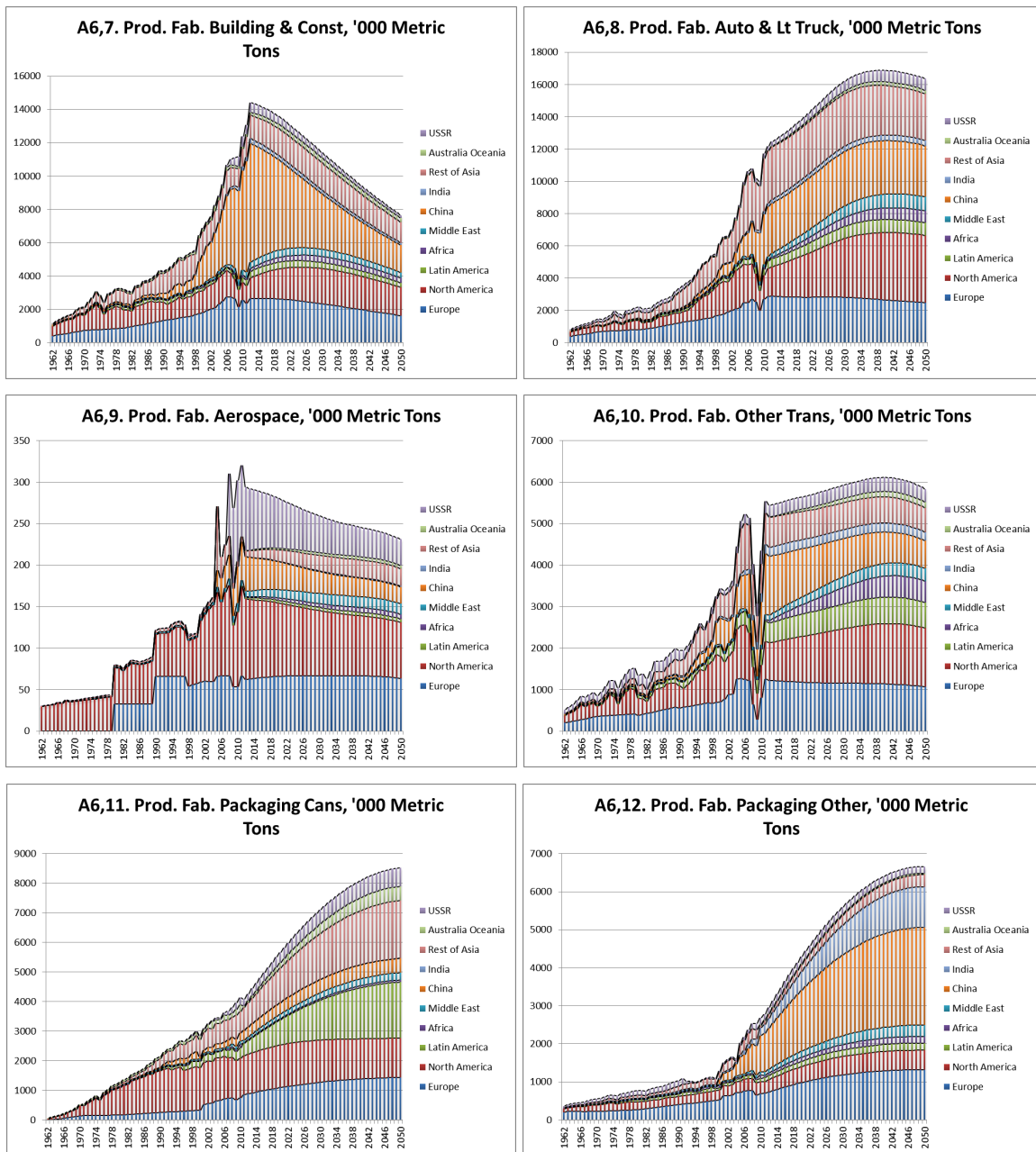
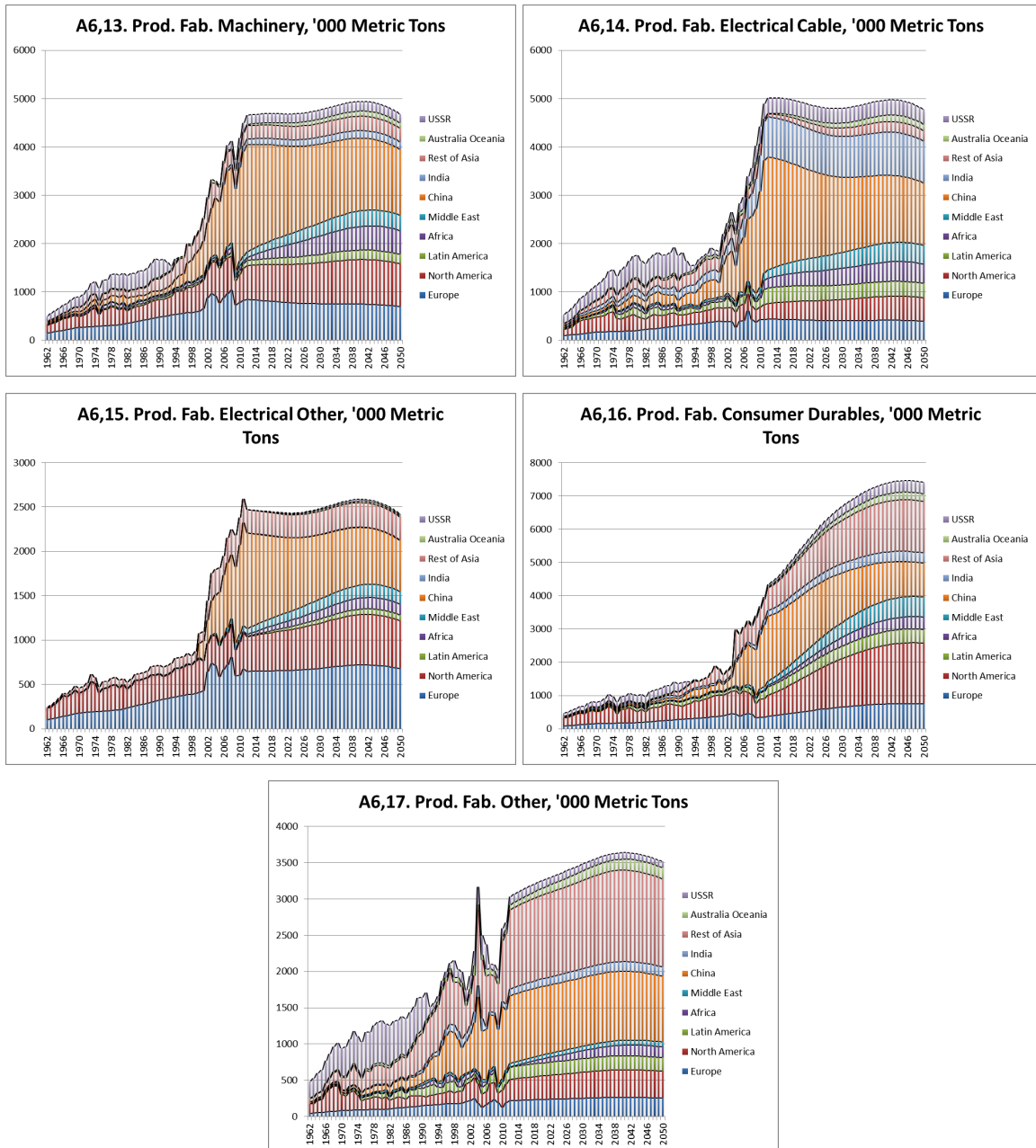


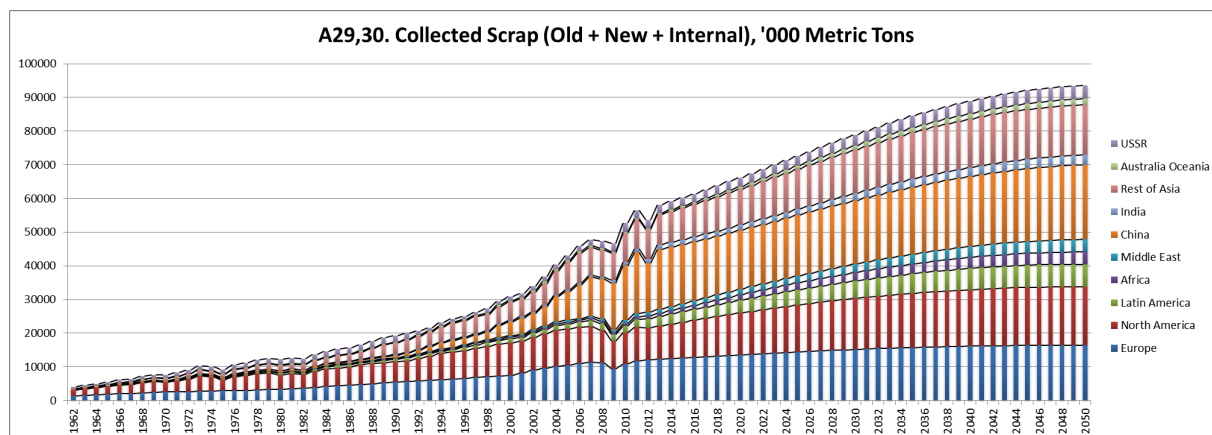
Figure 16. Scenario 1: Product Fabrication by Product Category by Region from 1962-2050





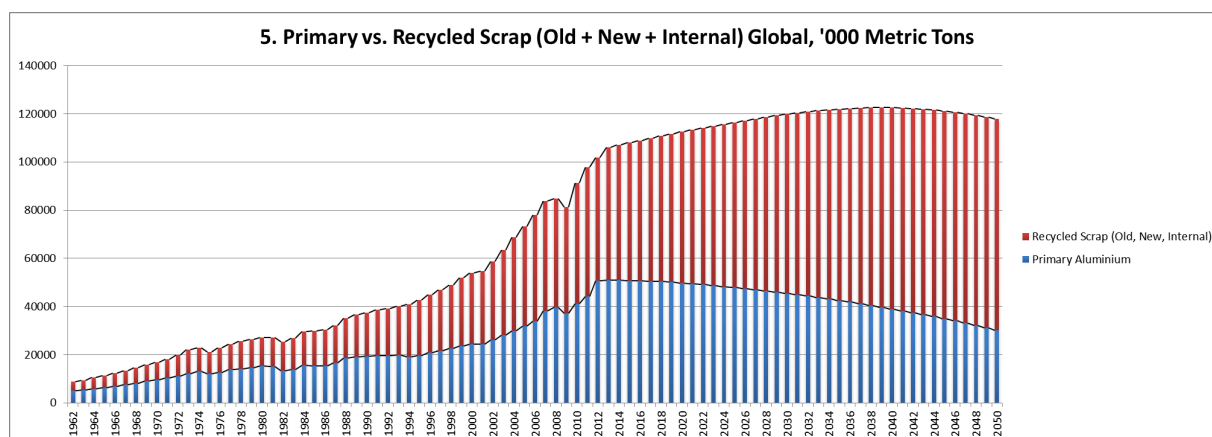
With the above level of product fabrication within each region and the assumptions made about scrap generation and collection, as described in section 2, the amount of old, new, and internal scrap collected within each region is shown in figure 17, reaching nearly 95 million metric tons by 2050. Since the fabrication takes place domestically in this scenario, the collected scrap is very similar to the old scrap generated curve in figure 11 and the product fabrication curve in figure 15 in terms of regional distribution.

Figure 17. Scenario 1: Total Collected Scrap for All Product Categories by Region from 1962-2050



After treatment of the collected scrap, the amount of recycled scrap available for reuse compared to the amount of primary aluminium required to meet global fabrication demand is shown in figure 18.

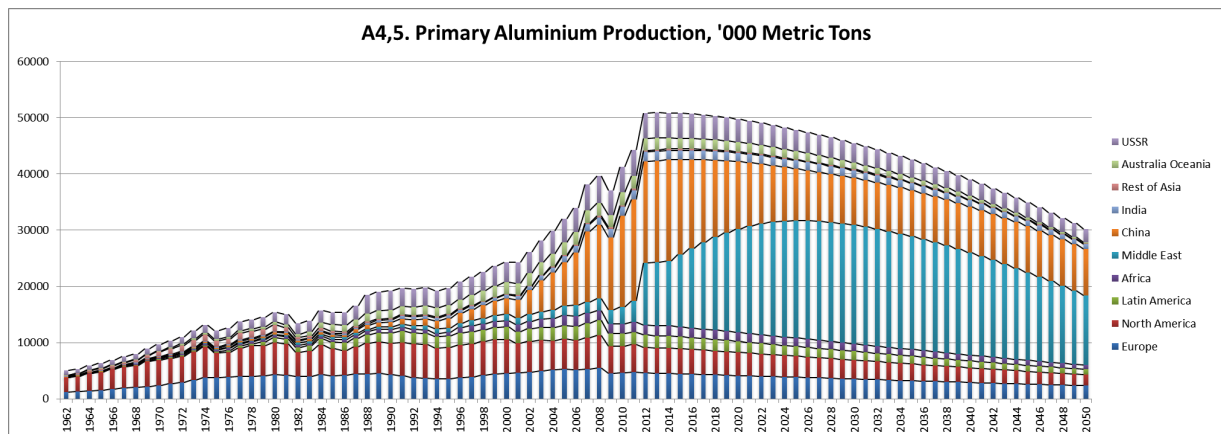
Figure 18. Scenario 1: Primary Aluminium vs. Recycled Scrap by Region from 1962-2050



In total, around 120 million metric tons of aluminium is required to meet fabrication demand in 2050. Given the assumptions made and the scenarios chosen for product fabrication and in-use stock, the large amount of collected scrap from 2012 to 2050 is expected to be recycled and reused, thereby reducing the amount of primary aluminium required to meet global demand. As figure 18 shows, the amount of recycled scrap steadily increases from around 54 million metric tons in 2011 to nearly 90 million metric tons in 2050, while on the other hand, the amount of primary aluminium demanded stabilizes at around 50 million metric tons in 2012 and 2013 before starting to decline gradually to 30 million metric tons in 2050.

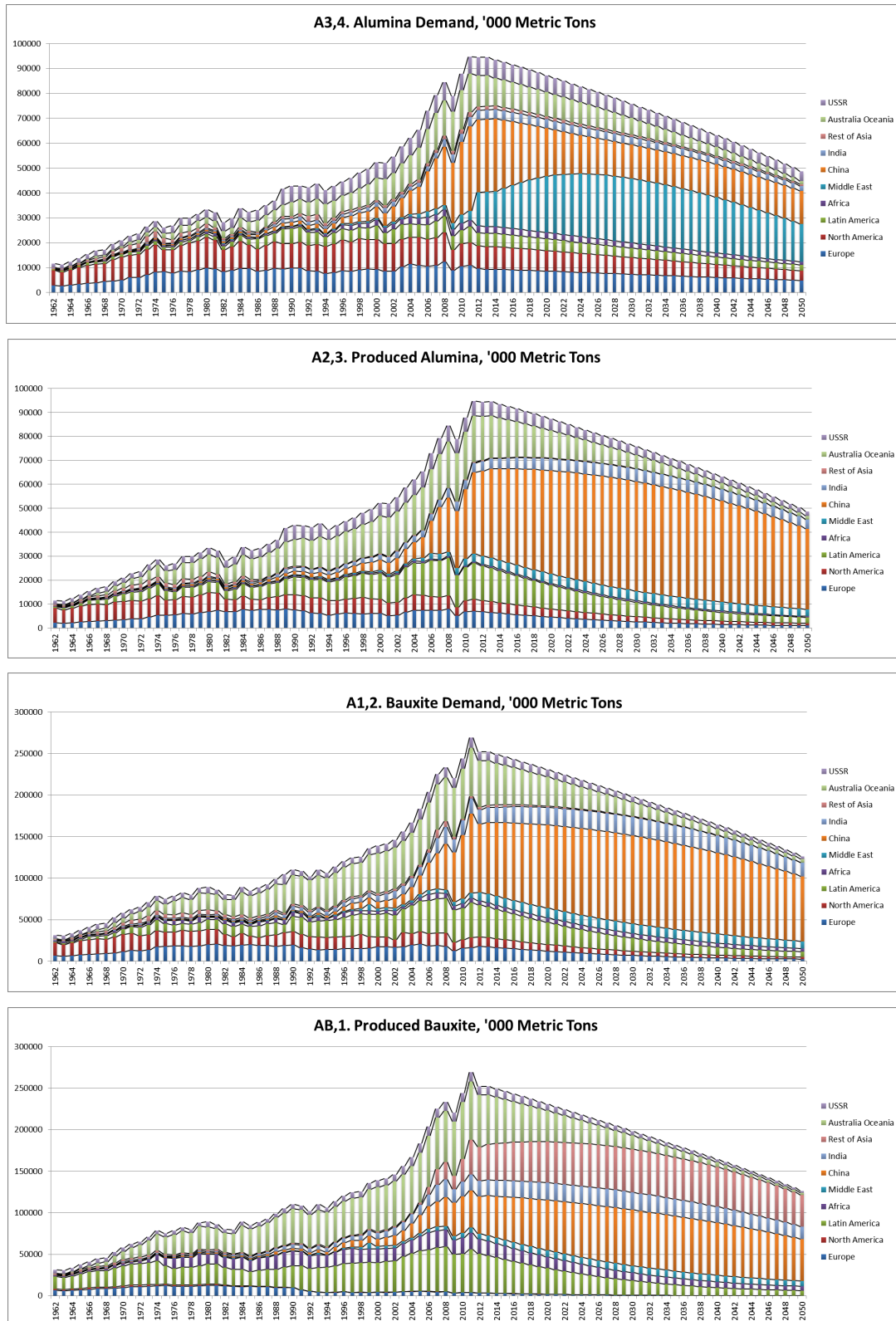
Going into greater detail with primary aluminium production, figure 19 highlights the distribution by region. Since the scenario assumes that the Middle East dominates primary aluminium production, the figure highlights how starting in 2011, the Middle East gradually increases its production of primary aluminium until around 2025, when it maintains the dominant position as the main producer of primary aluminium until 2050, taking over from China.

Figure 19. Scenario 1: Primary Aluminium Production by Region from 1962-2050



The declining level of primary aluminium in this scenario will impact the amount of alumina and bauxite demanded and produced. As figure 20 shows, the alumina demand to meet the level of primary aluminium production also declines from around 95 million metric tons in 2011 to 50 million metric tons in 2050. Since the Middle East is the dominant producer of primary aluminium in this scenario, the majority of the demand comes from this region. However, based on the scenarios and assumptions regarding alumina production described in section 2.2.2.3., China is the dominant producer of alumina to meet this demand. Looking at bauxite, the bauxite demanded to produce the necessary level of alumina declines from around 260 million metric tons in 2011 to less than 150 million metric tons in 2050, with demand mainly in China as it is the dominant producer of alumina. To meet this demand, based on the scenarios and assumptions regarding bauxite production in section 2.2.2.3., Rest of Asia and China become the major producers of bauxite starting from around 2015 to 2050, gradually stealing share away from Australia and Oceania and Latin America.

Figure 20. Scenario 1: Alumina and Bauxite Demand and Production by Region from 1962-2050



3.2.2. Scenario 2: Middle East dominates primary AL production, Fabrication integrated with primary AL production

The second scenario for future aluminium production and final product fabrication assumes that by 2050 future primary aluminium production is dominated by the Middle East and by 2050 fabrication of final products containing aluminium is integrated with primary aluminium production. The global level of product fabrication does not change, since the model assumes that all aluminium product demand is met, but the regional distribution of product fabrication in this scenario is different. Since fabrication is integrated with primary aluminium production and Middle East dominates primary aluminium production, the Middle East is the main region for product fabrication, as shown in figure 21 in total and figure 22 by product category.

Figure 21. Scenario 2: Total Product Fabrication for All Product Categories by Region from 1962-2050

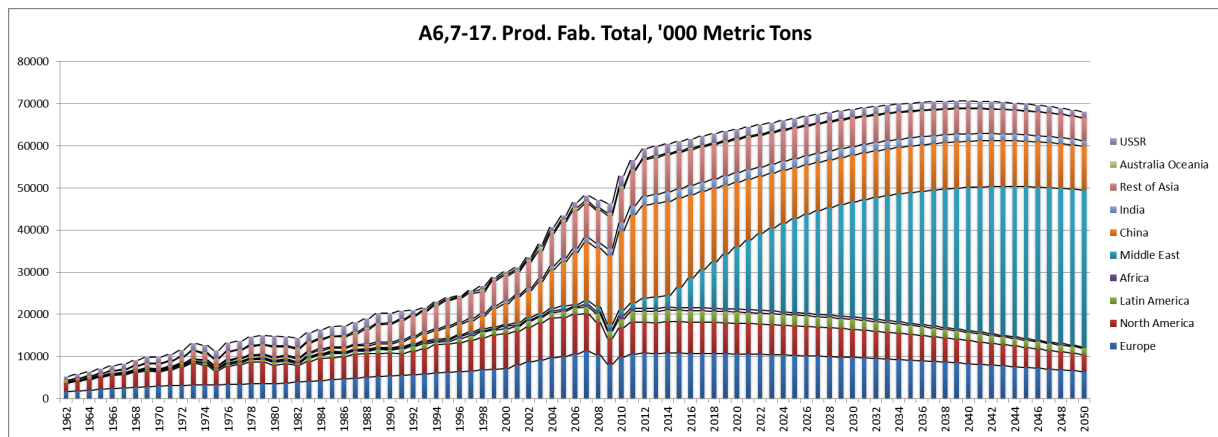
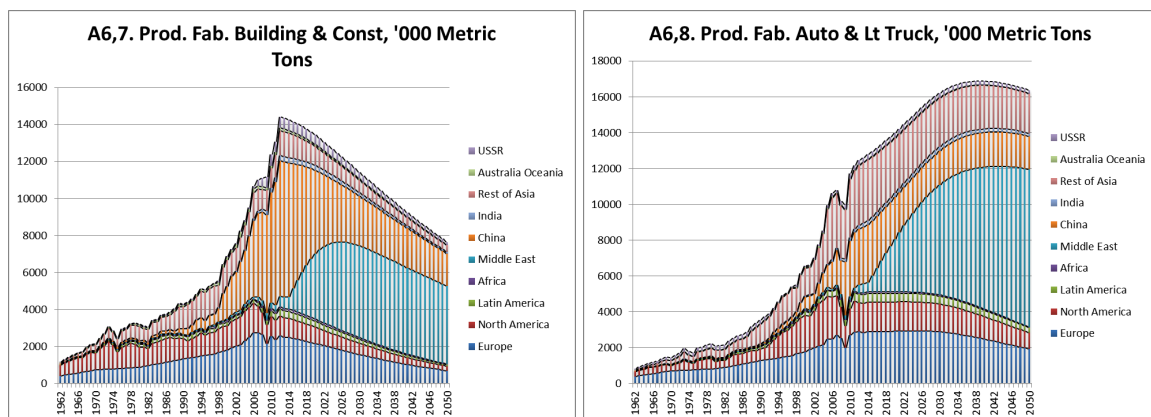
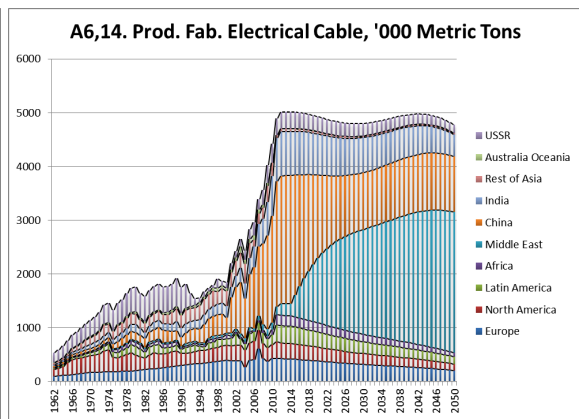
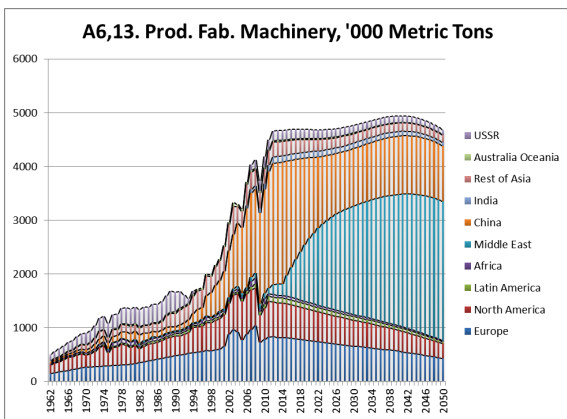
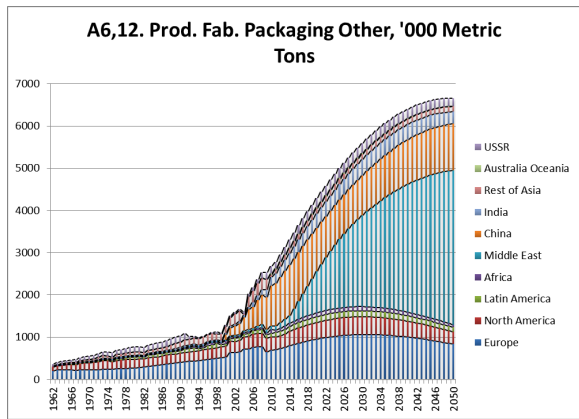
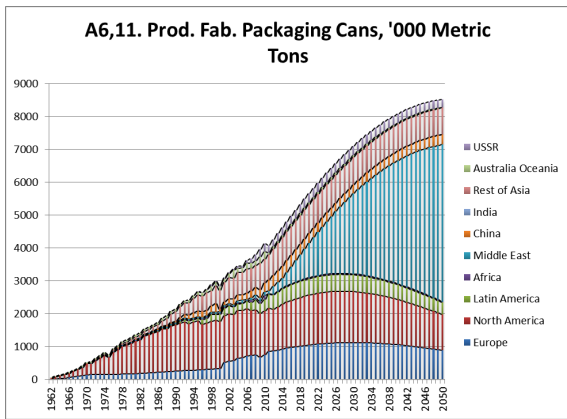
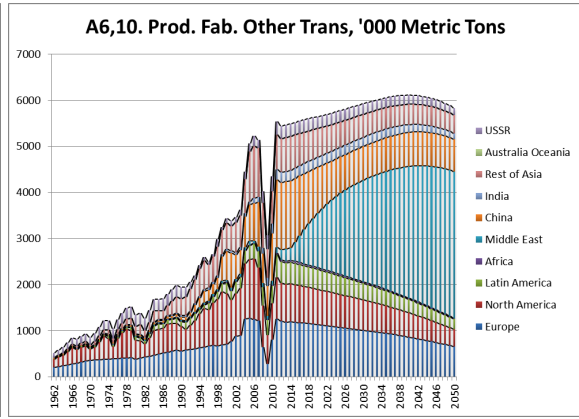
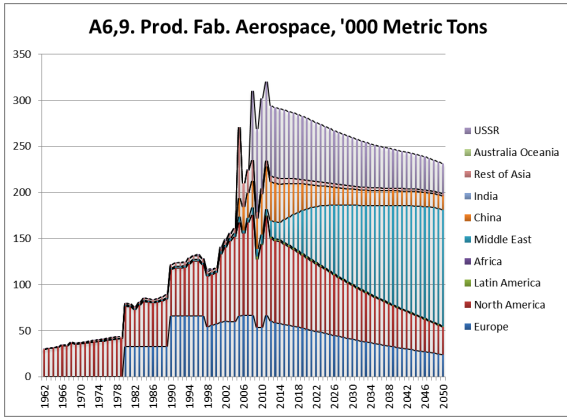
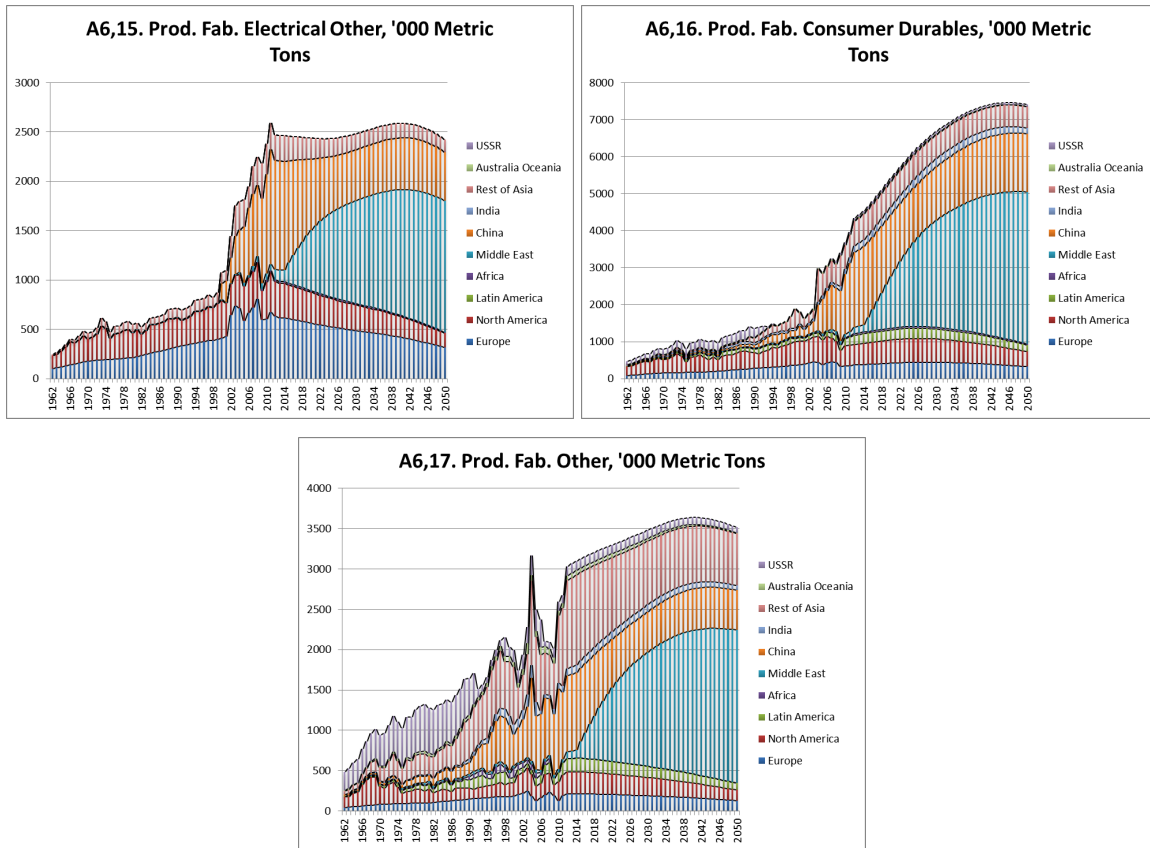


Figure 22. Scenario 2: Product Fabrication by Product Category by Region from 1962-2050







Given this regional breakdown of product fabrication, the amount of old, new, and internal scrap collected within each region is shown in figure 23. The amount of collected scrap is lower than in the first scenario, only reaching around 85 million metric tons by 2050. There is a greater share of scrap coming from the Middle East compared to the first scenario in figure 17, since the majority of product fabrication takes place there leading to greater internal and new scrap.

Figure 23. Scenario 2: Total Collected Scrap for All Product Categories by Region from 1962-2050

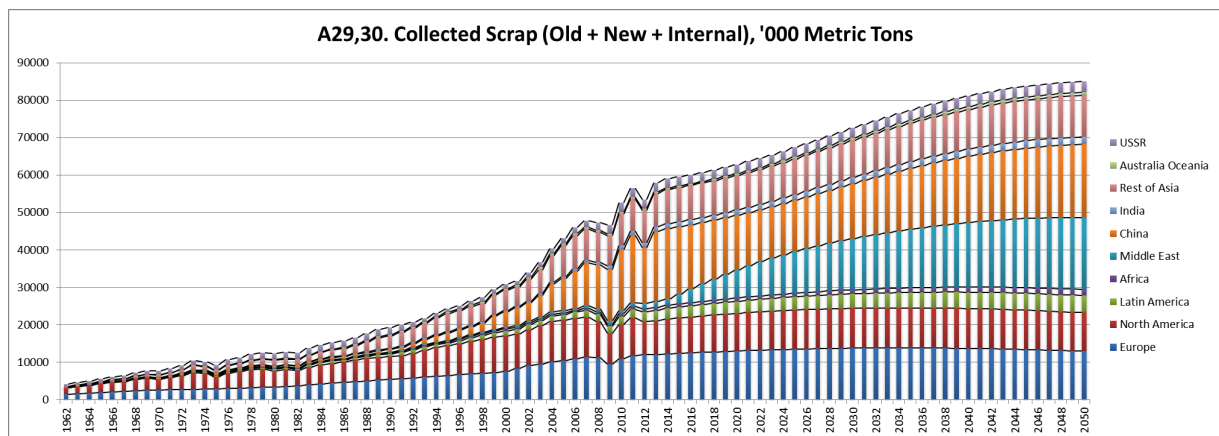
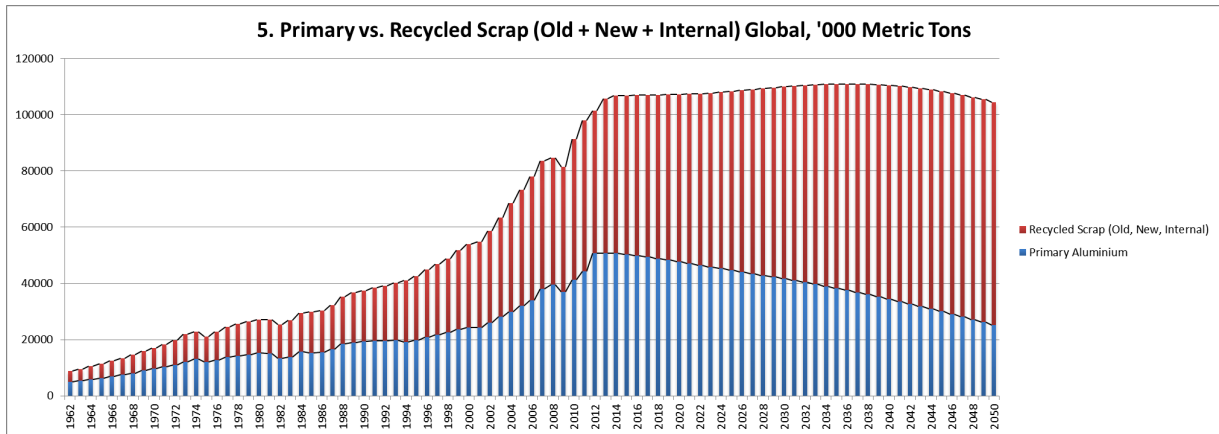


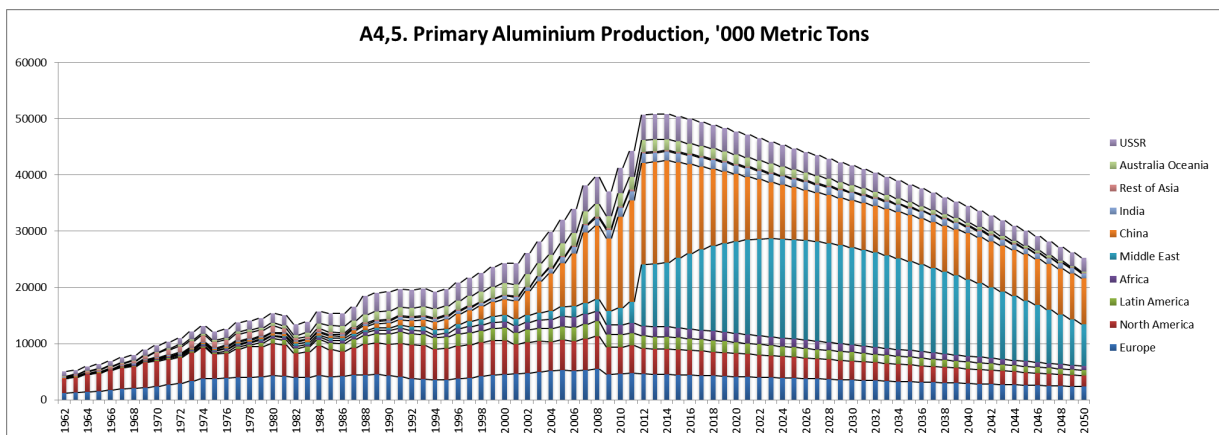
Figure 24. Scenario 2: Primary Aluminium vs. Recycled Scrap by Region from 1962-2050



The amount of recycled scrap available for reuse compared to the amount of primary aluminium required to meet global fabrication demand is shown in figure 24. Due to the regional fabrication assumptions made in section 2, making the Middle East more efficient in product fabrication, the total amount of aluminium required to meet fabrication demand is much lower in this scenario, around 110 million metric tons between 2011 and 2050, compared to the scenario 1 which is around 120 million metric tons. The amount of primary aluminium required to meet global demand declines to 25 million metric tons in 2050. On the other hand, the amount of scrap available for reuse grows to 80 million metric tons in 2050.

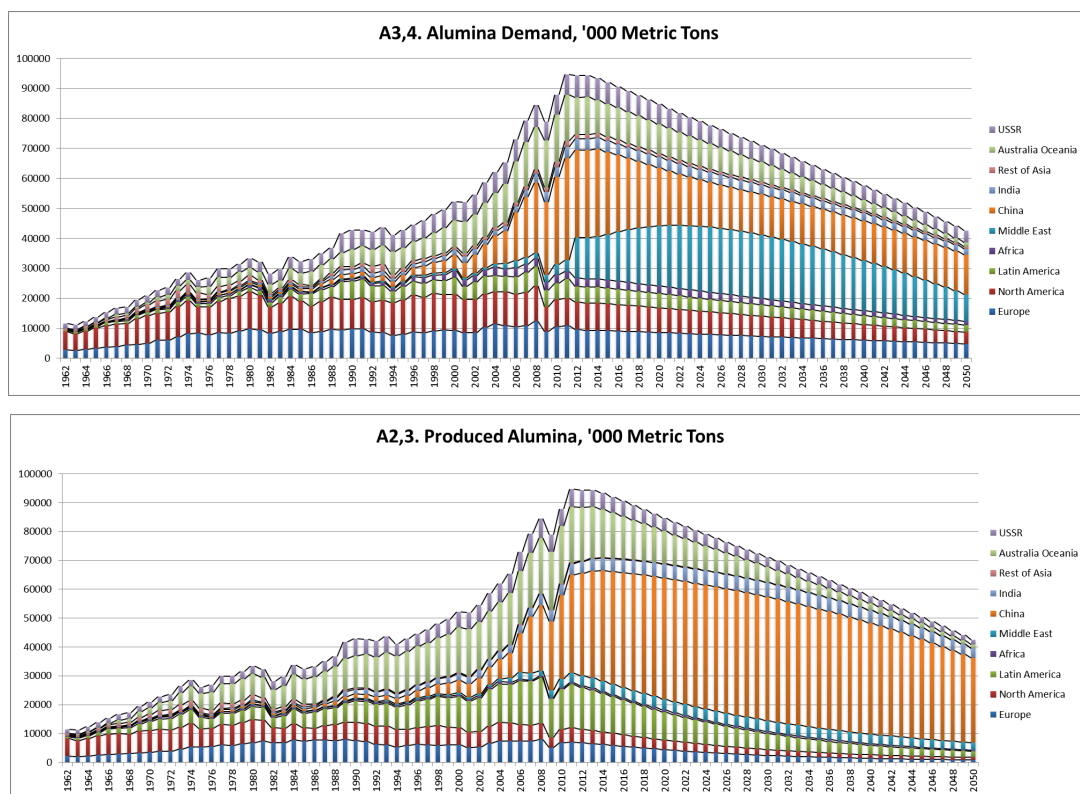
The regional breakdown of primary aluminium production is shown in figure 25. Like the first scenario, this scenario also assumes that the Middle East dominates primary aluminium production. Thus, as in figure 19, figure 25 shows the Middle East gradually increases its production of primary aluminium taking over China by 2025.

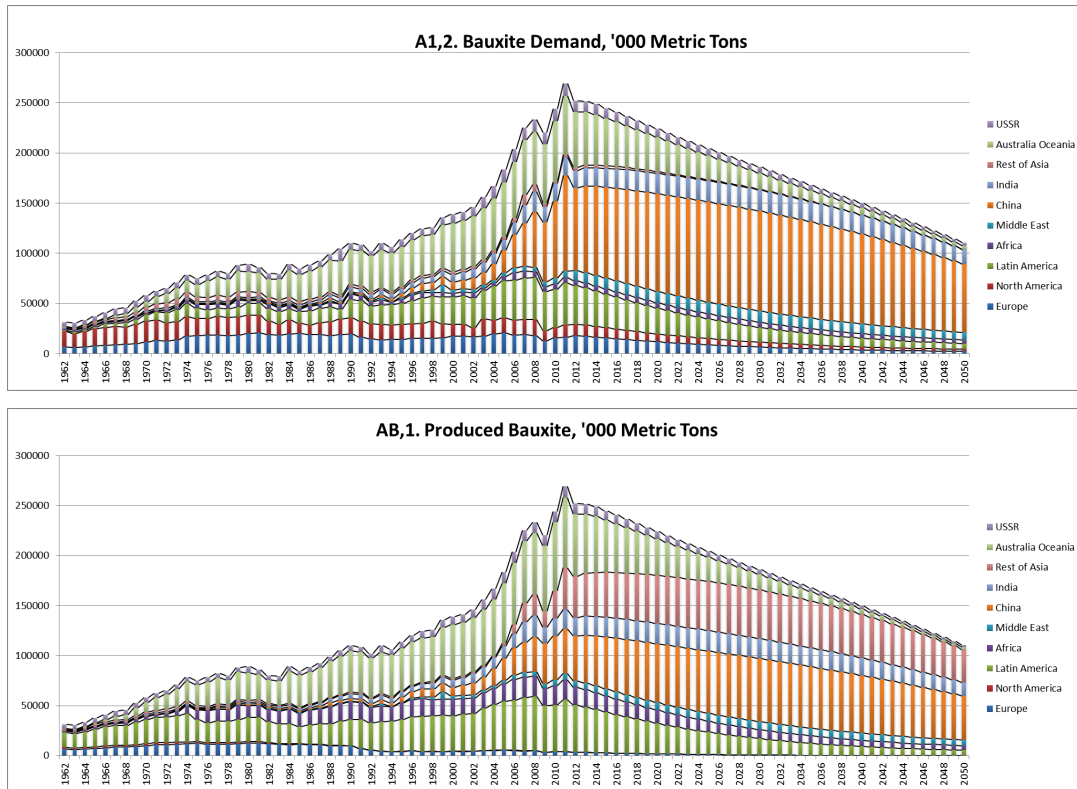
Figure 25. Scenario 2: Primary Aluminium Production by Region from 1962-2050



The impact of the primary aluminium production in this scenario is shown in figure 26. The alumina demand to meet the level of primary aluminium production declines from around 95 million metric tons in 2011 to 40 million metric tons in 2050. Once again, since the Middle East is the dominant producer of primary aluminium in this scenario, the majority of the demand comes from this region. To meet this demand for alumina, alumina production primarily takes place in China based on the assumptions made in section 2. In this scenario, bauxite demanded to produce the necessary level of alumina declines from around 260 million metric tons in 2011 to around 100 million metric tons in 2050, with demand mainly in China as it is the dominant producer of alumina. As in the first scenario, to meet this bauxite demand Rest of Asia and China become the major producers of bauxite starting from around 2015 to 2050, gradually stealing share away from Australia and Oceania and Latin America.

Figure 26. Scenario 2: Alumina and Bauxite Demand and Production by Region from 1962-2050





3.2.3. Scenario 3: China dominates primary AL production, Fabrication follows domestic demand

The third scenario for future aluminium production and final product fabrication assumes that by 2050 future primary aluminium production is dominated by the China and by 2050 fabrication of final products containing aluminium is satisfied by domestic facilities that meet domestic demand. As in the first two scenarios, the global level of product fabrication does not change, since the model assumes that all aluminium product demand is met. Figure 27 shows the product fabrication of all the product categories by region. Like the first scenario, domestic demand within each region is assumed to be met domestically by 2050, thus the regional breakdown of total product fabrication between the 10 regions is exactly identical to figure 15. The fabrication charts by product category, shown in figure 28, is also the same as the first scenario, shown in figure 16.

Figure 27. Scenario 3: Total Product Fabrication for All Product Categories by Region from 1962-2050

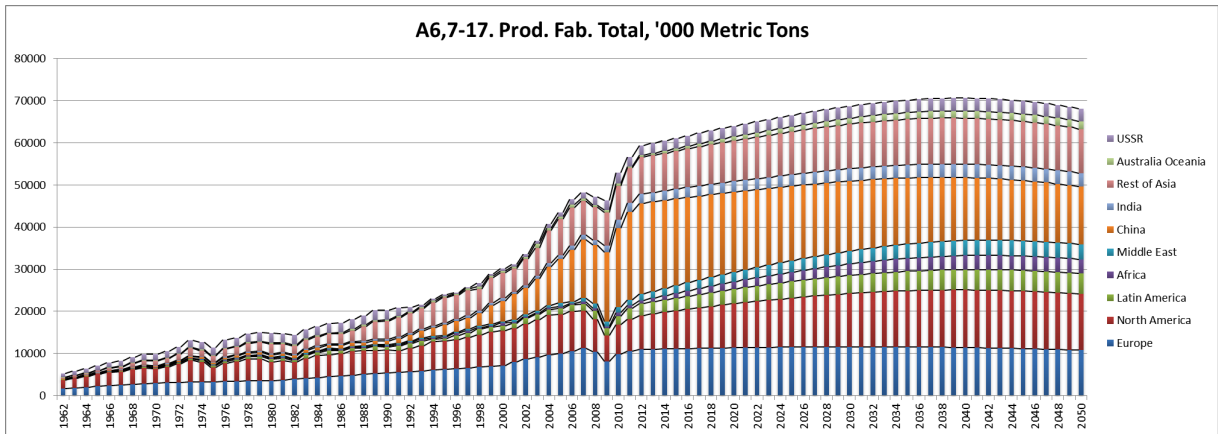
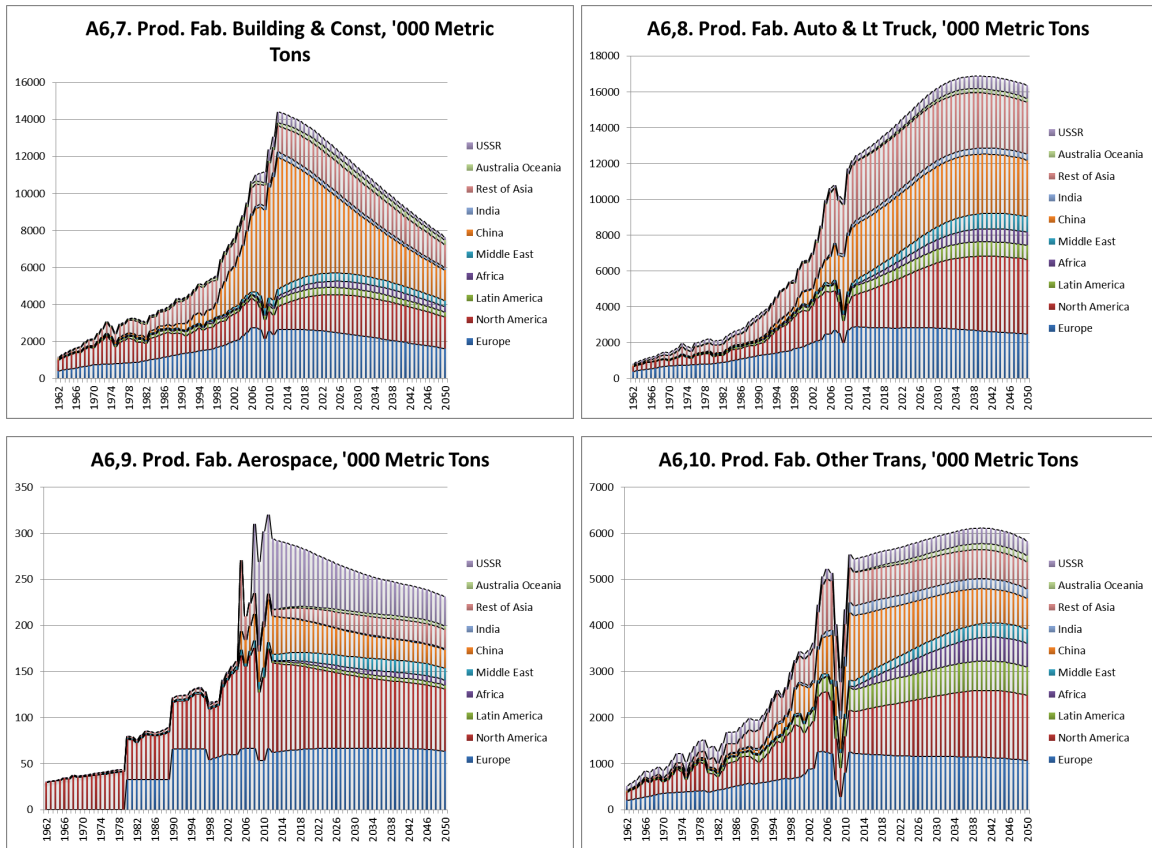
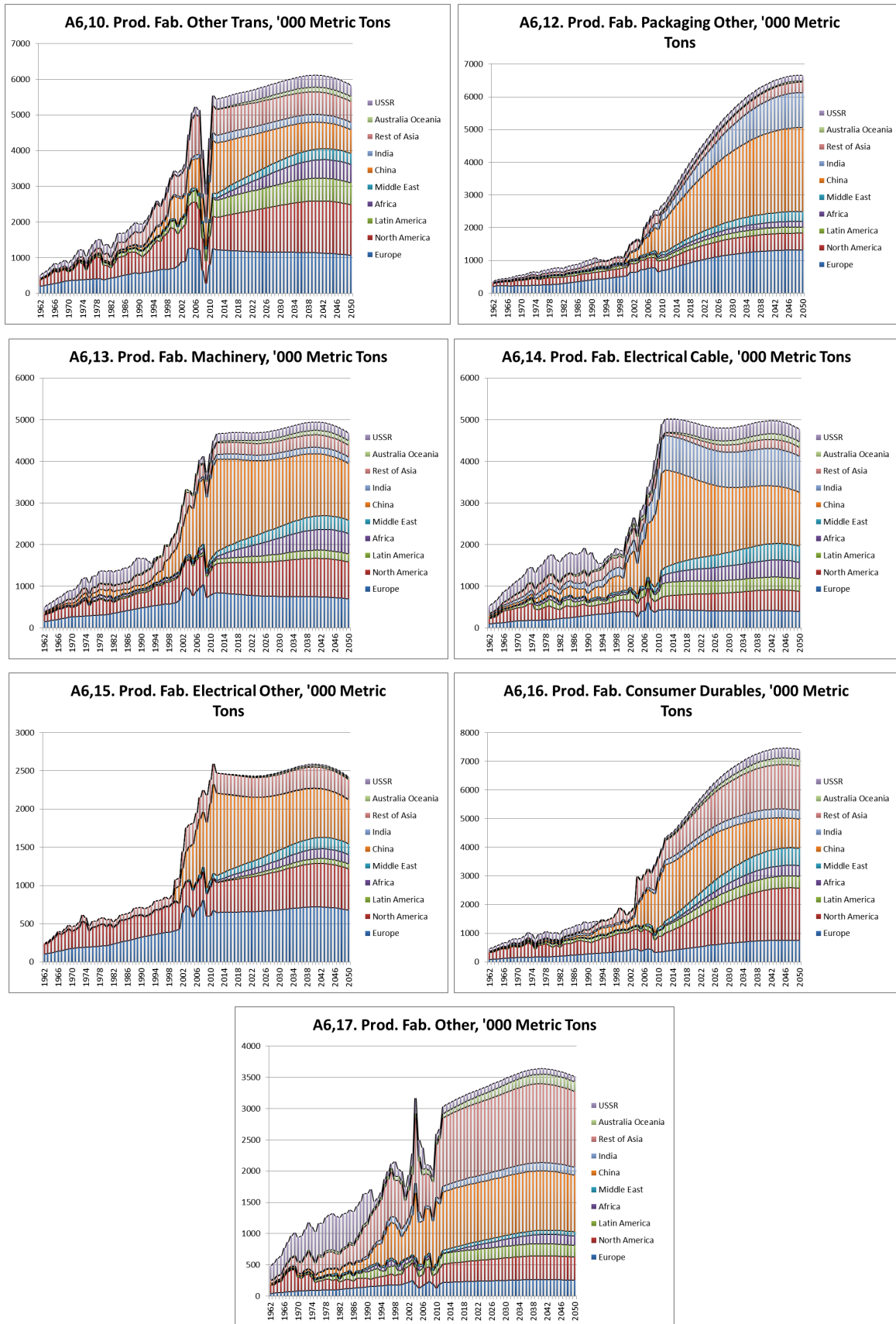


Figure 28. Scenario 3: Product Fabrication by Product Category by Region from 1962-2050

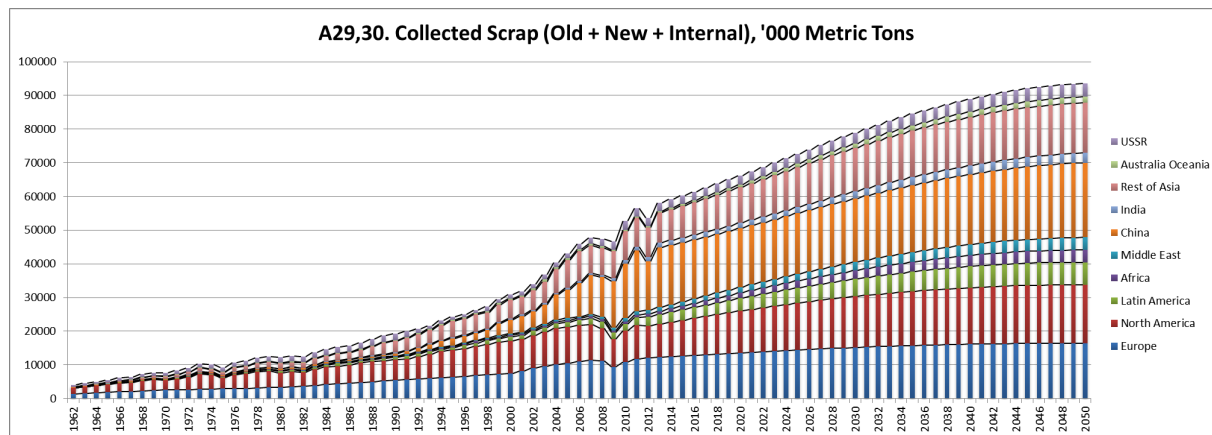




The amount of old, new, and internal scrap collected within each region is shown in figure 29, reaching nearly 95 million metric tons by 2050. Since the fabrication takes place

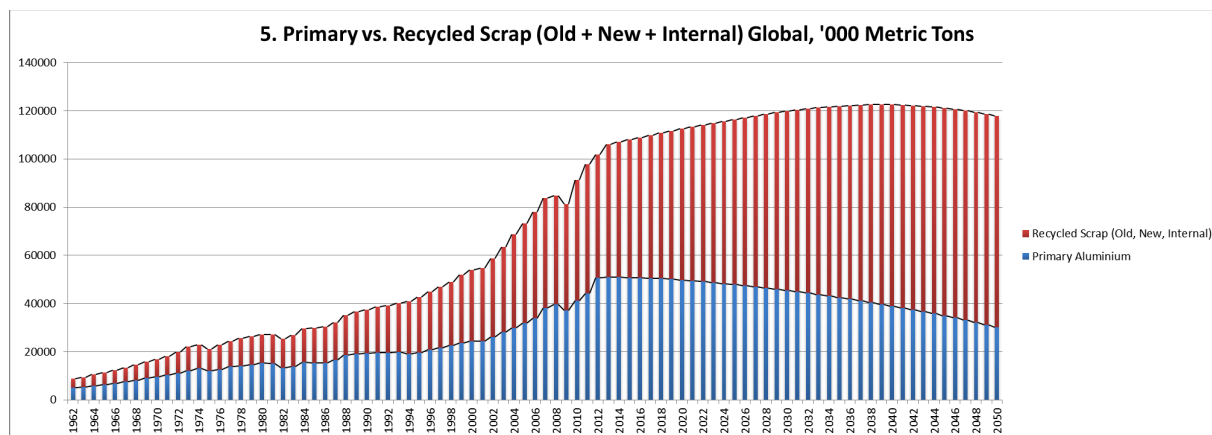
domestically in this scenario, both the distribution and volume of scrap collected is the same as figure 17 in the first scenario.

Figure 29. Scenario 3: Total Collected Scrap for All Product Categories by Region from 1962-2050



Likewise, the amount of recycled scrap available for reuse compared to the amount of primary aluminium required to meet global fabrication demand, shown in figure 30, is also identical to figure 18 from the first scenario. As before, around 120 million metric tons of aluminium is required to meet fabrication demand in 2050.

Figure 30. Scenario 3: Primary Aluminium vs. Recycled Scrap by Region from 1962-2050

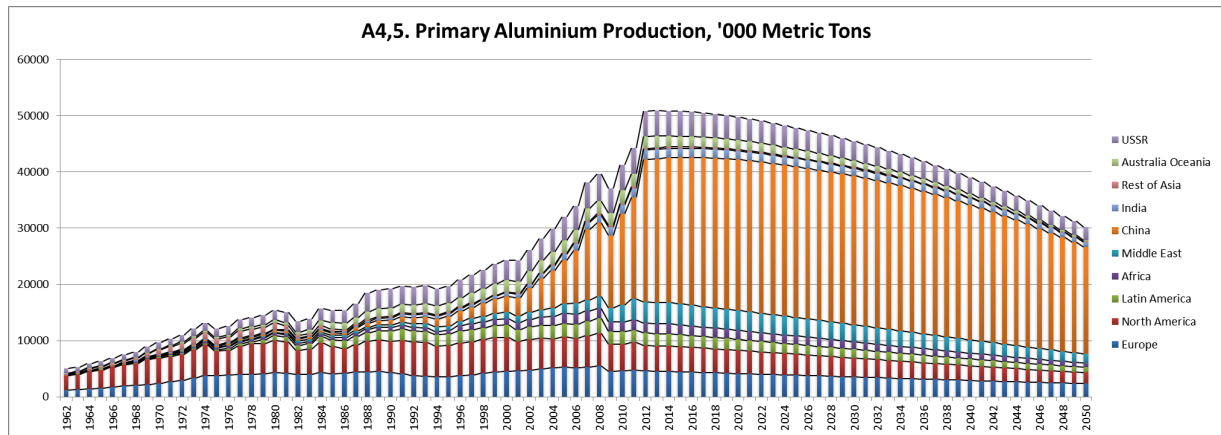


Just as in the first scenario, the amount of recycled scrap steadily increases from around 54 million metric tons in 2011 to nearly 90 million metric tons in 2050, while the amount of primary aluminium demanded declines from around 50 million metric tons in 2011 to 30 million metric tons in 2050.

However, when it comes to primary aluminium production, this scenario differs from the first scenario by assuming that China dominates primary aluminium production. Figure 31

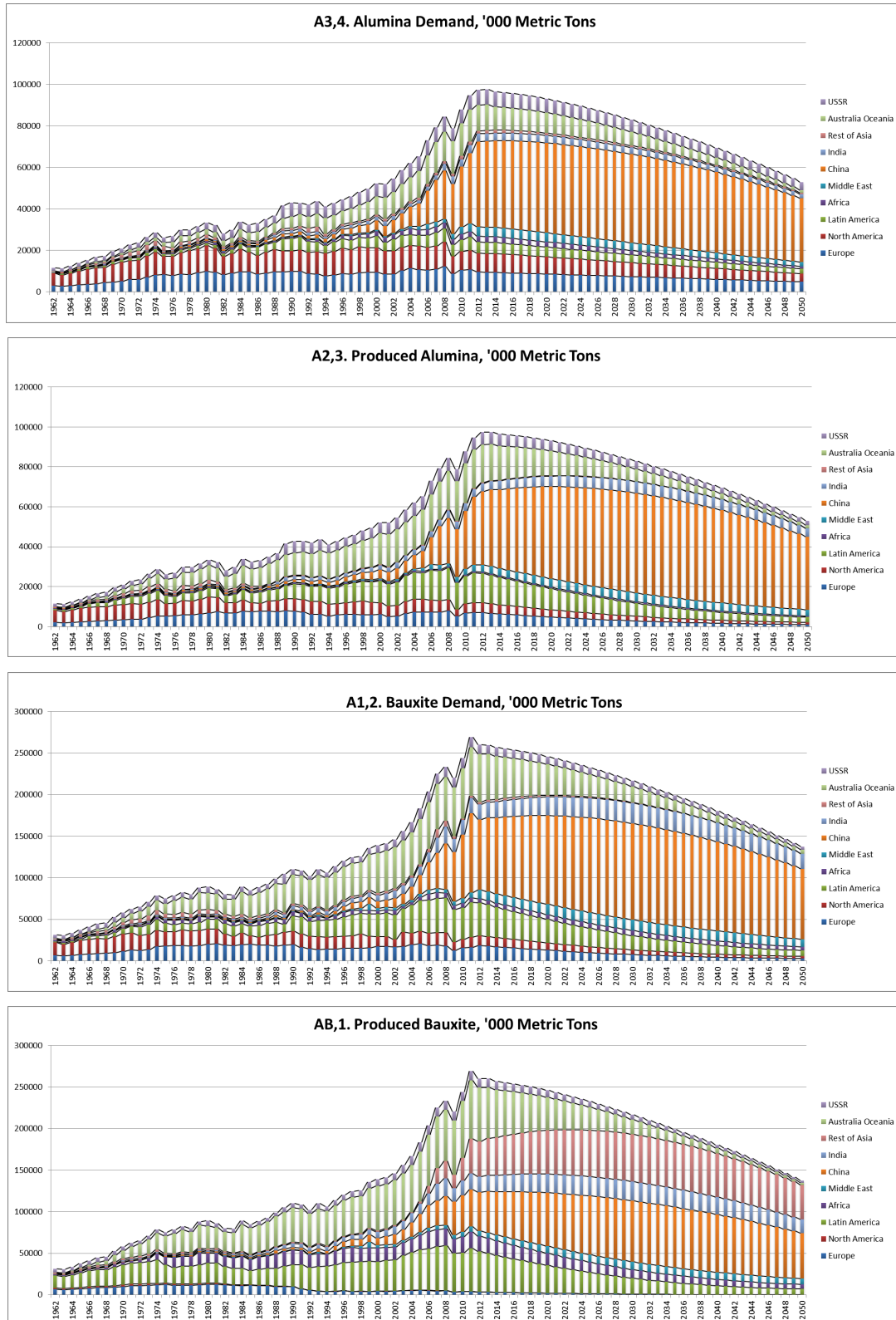
shows the breakdown of primary aluminium production by region. As China already was beginning to dominate primary aluminium production from 2005 to 2011, the assumptions for this scenario continue to increase China's share of primary aluminium production from 2012 to 2050.

Figure 31. Scenario 3: Primary Aluminium Production by Region from 1962-2050



The effect of primary aluminium production in this scenario on alumina and bauxite is shown in figure 32. Since the level of primary aluminium production is the same as the first scenario, the total alumina demand is also the same, declining from around 95 million metric tons in 2011 to 50 million metric tons in 2050. However, since China is the dominant producer of primary aluminium in this scenario, the majority of the alumina demand comes from China. Based on the scenario for alumina production, China is the dominant producer of alumina and thus has the greatest demand for bauxite, based on the assumptions made. The level of bauxite demand globally is identical to scenario 1, from around 260 million metric tons in 2011 to less than 150 million metric tons in 2050. As before, based on the assumptions made, to meet this bauxite demand Rest of Asia and China become the major producers of bauxite starting from around 2015 to 2050, gradually stealing share away from Australia and Oceania and Latin America.

Figure 32. Scenario 3: Alumina and Bauxite Demand and Production by Region from 1962-2050



3.2.4. Scenario 4: China dominates primary AL production, Fabrication integrated with primary AL production

The last scenario for future aluminium production and final product fabrication assumes that by 2050 future primary aluminium production is dominated by the China and by 2050 fabrication of final products containing aluminium is integrated with primary aluminium production. As in the earlier scenarios, the global level of product fabrication does not change, since the model assumes that all aluminium product demand is met. This scenario is similar to the second scenario, since it assumes that fabrication is integrated with primary aluminium production. However, in this scenario, China is the dominant producer of primary aluminium. Thus, when looking at the regional distribution, as figure 33 and figure 34 show, China overwhelmingly dominates the product fabrication for all the product categories

Figure 33. Scenario 4: Total Product Fabrication for All Product Categories by Region from 1962-2050

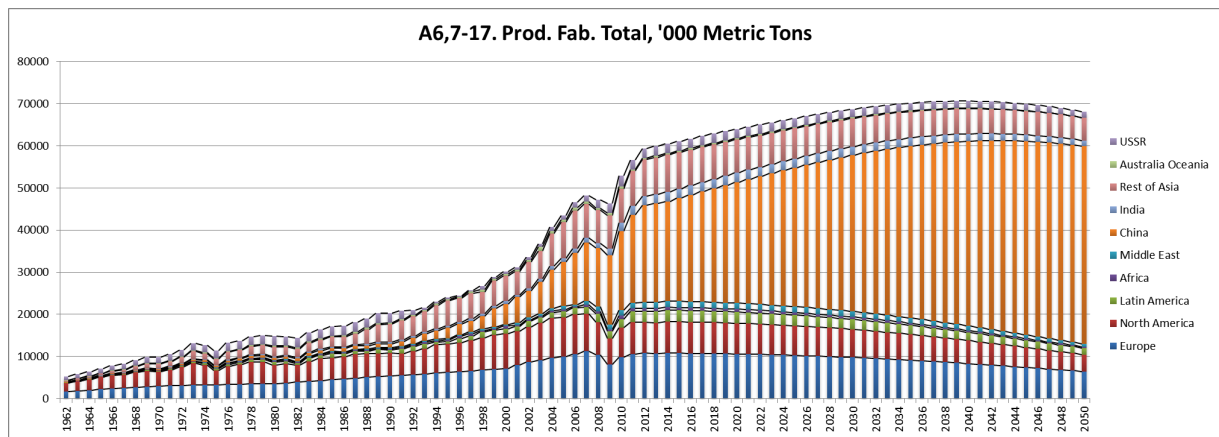
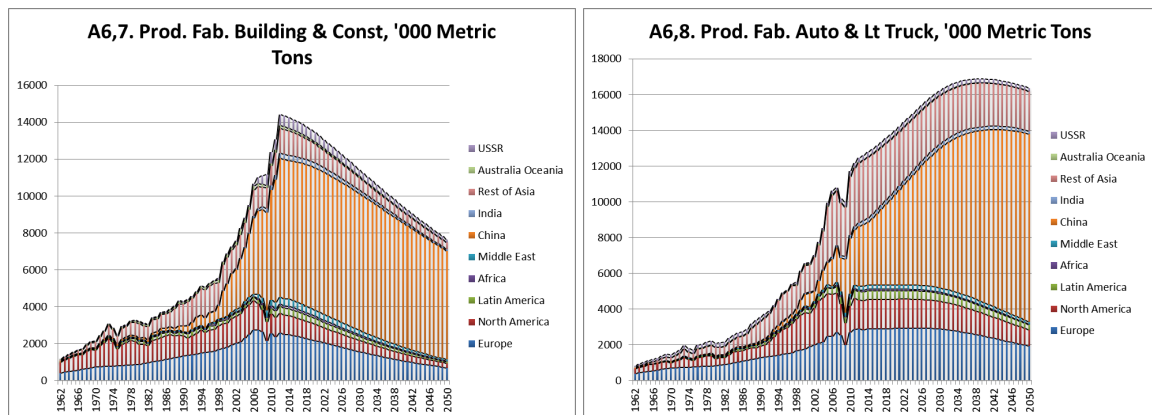
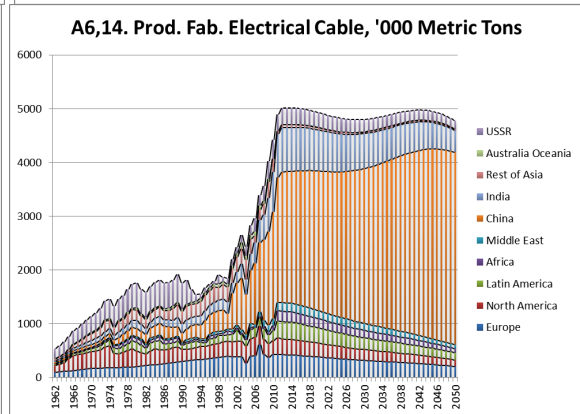
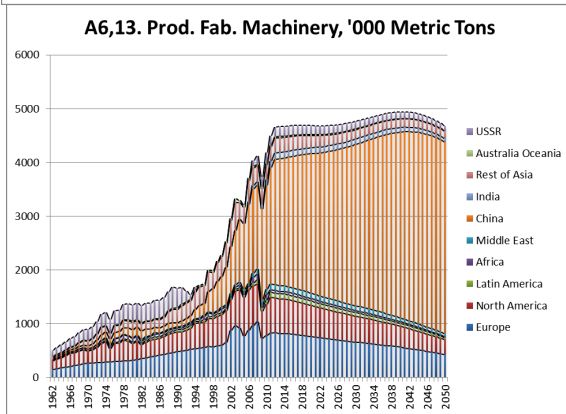
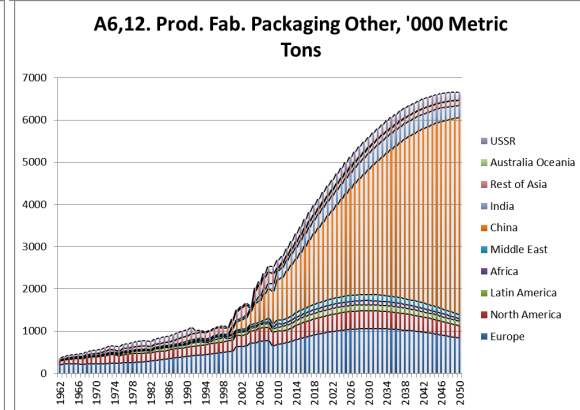
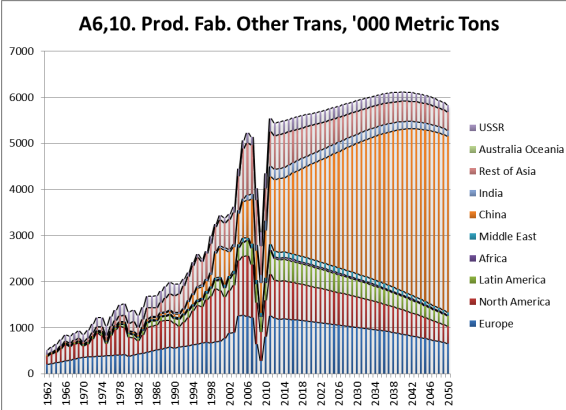
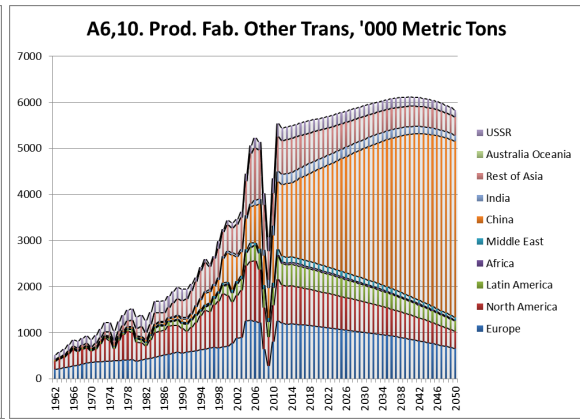
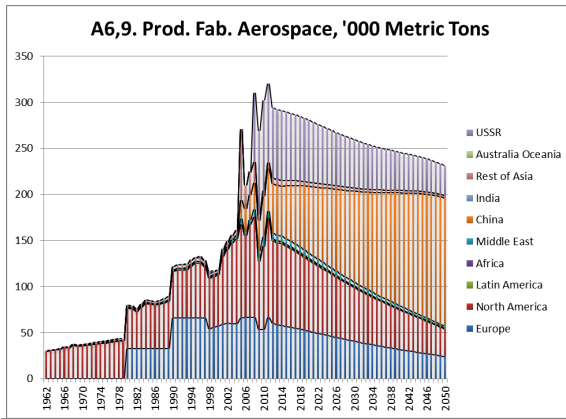
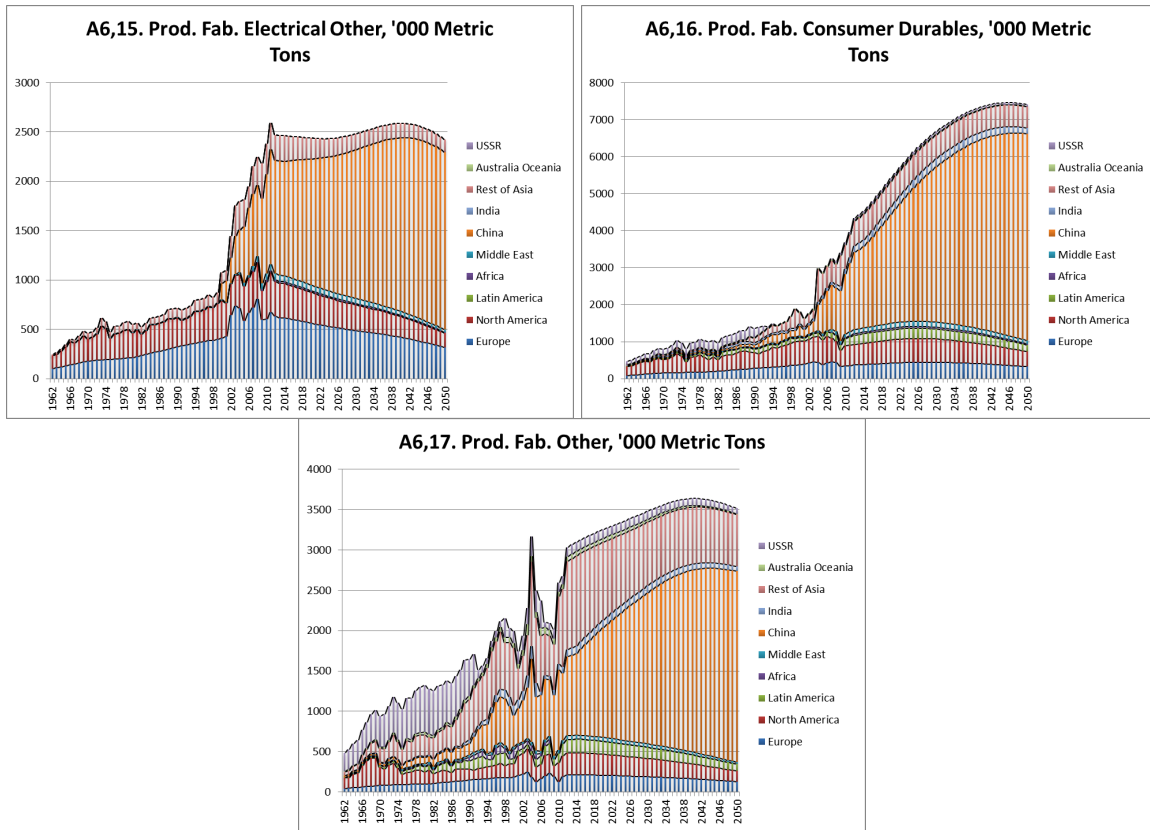


Figure 34. Scenario 4: Product Fabrication by Product Category by Region from 1962-2050

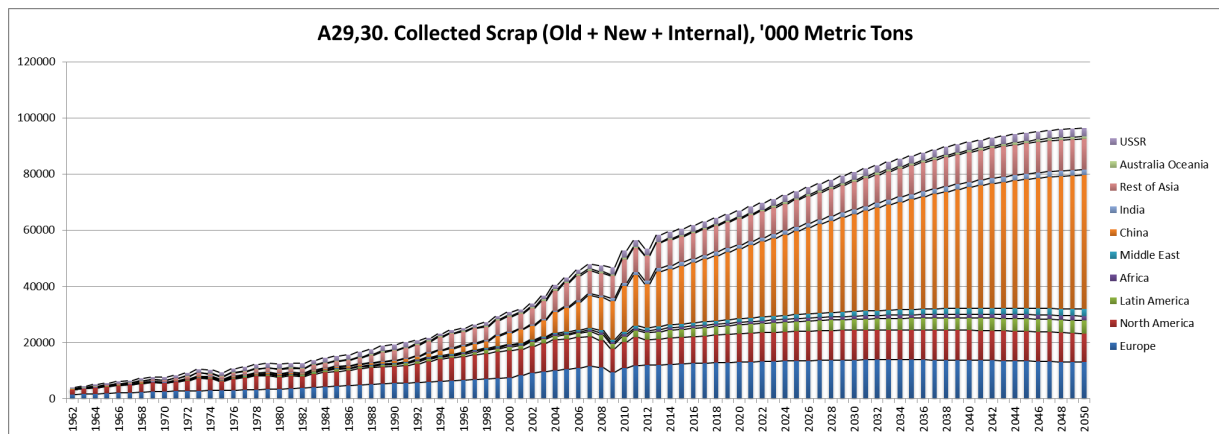






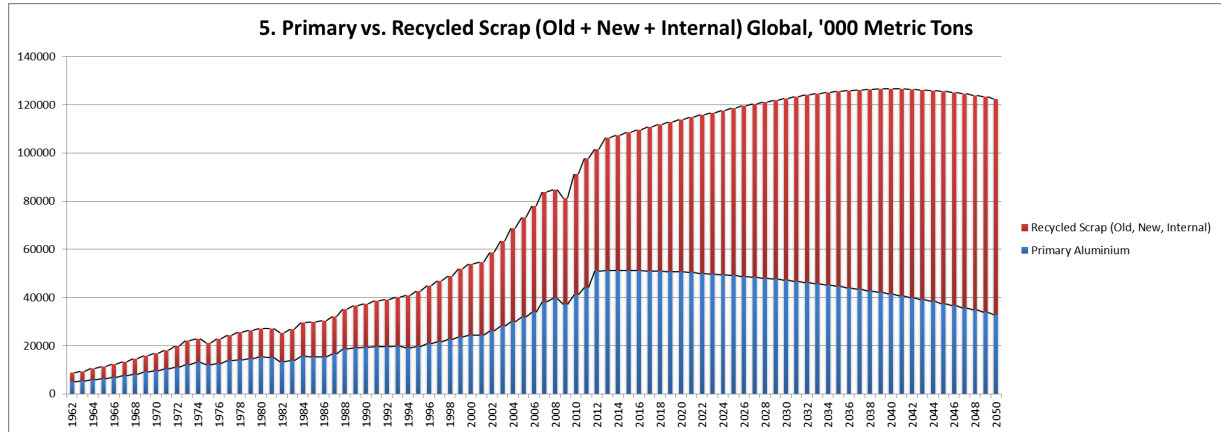
Based on this regional breakdown of product fabrication, the amount of old, new, and internal scrap collected within each region is shown in figure 35. From the assumptions about scrap generation made in section 2, the amount of collected scrap in this scenario is the highest of all the scenarios, reaching nearly 100 million metric tons by 2050. The largest share of the scrap comes from China, as it is the region where the majority of product fabrication takes place.

Figure 35. Scenario 4: Total Collected Scrap for All Product Categories by Region from 1962-2050



The amount of scrap recycled and available for reuse compared to the amount of primary aluminium required to meet global demand for fabrication is shown in figure 36.

Figure 36. Scenario 4: Primary Aluminium vs. Recycled Scrap by Region from 1962-2050



The regional fabrication assumptions made in section 2 assumed that China is less efficient in product fabrication, thus the total amount of aluminium required to meet fabrication demand is the highest in this scenario, reaching a maximum of over 125 million metric tons. The amount of primary aluminium required to meet global demand declines to around 33 million metric tons in 2050, while the amount of scrap available for reuse grows to 90 million metric tons in 2050.

As in scenario 3, this scenario assumes that China dominates primary aluminium production. Figure 37 shows the breakdown of primary aluminium production by region, which looks very similar to figure 31 in scenario 3.

Figure 37. Scenario 4: Primary Aluminium Production by Region from 1962-2050

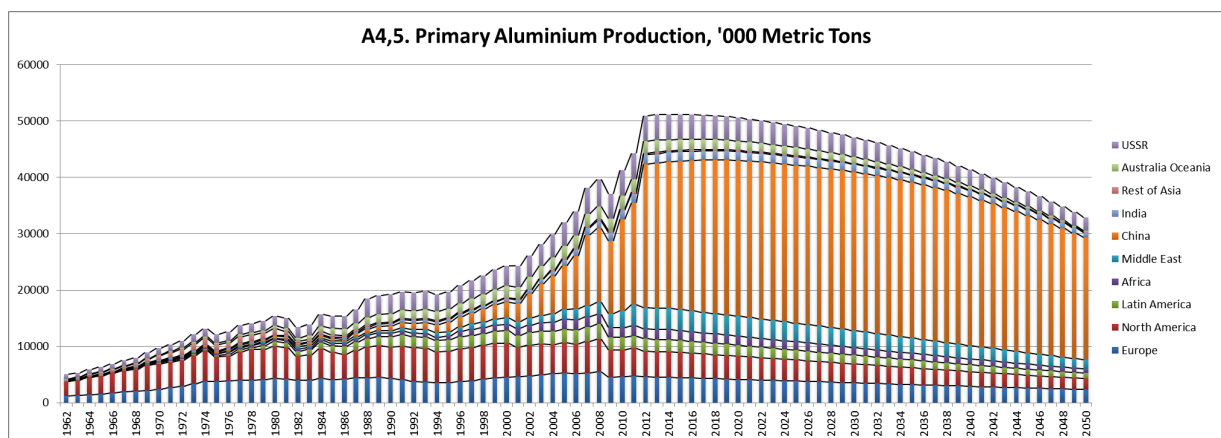
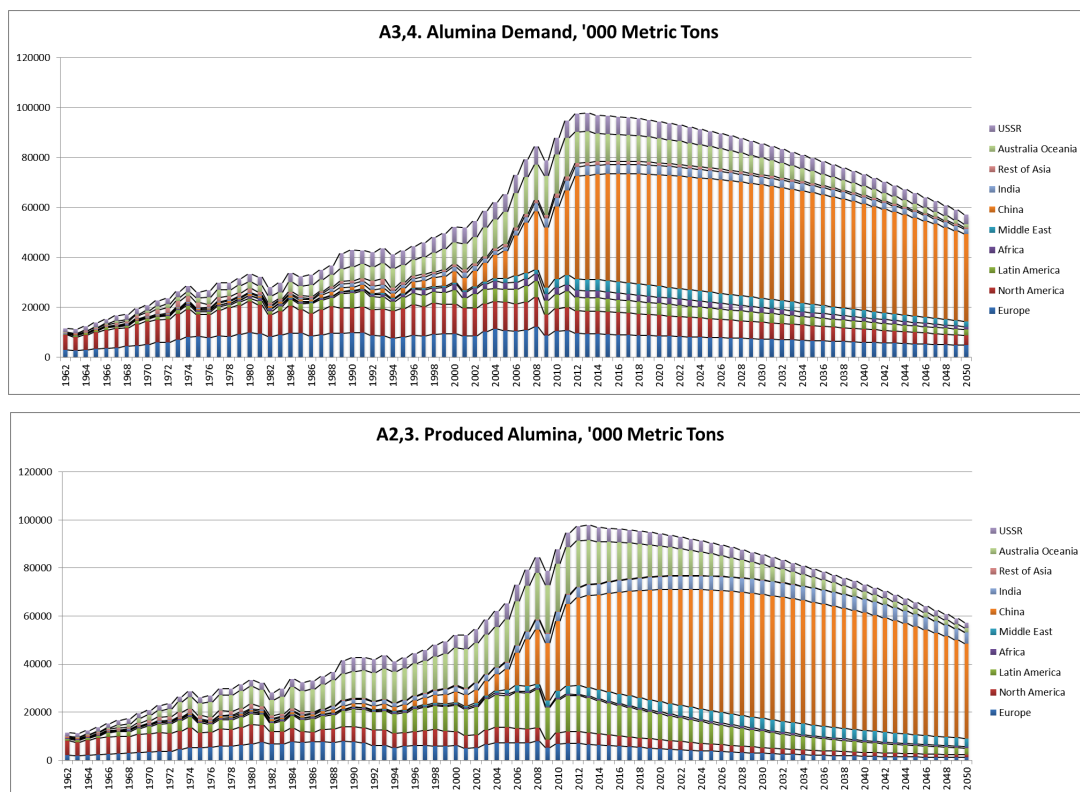
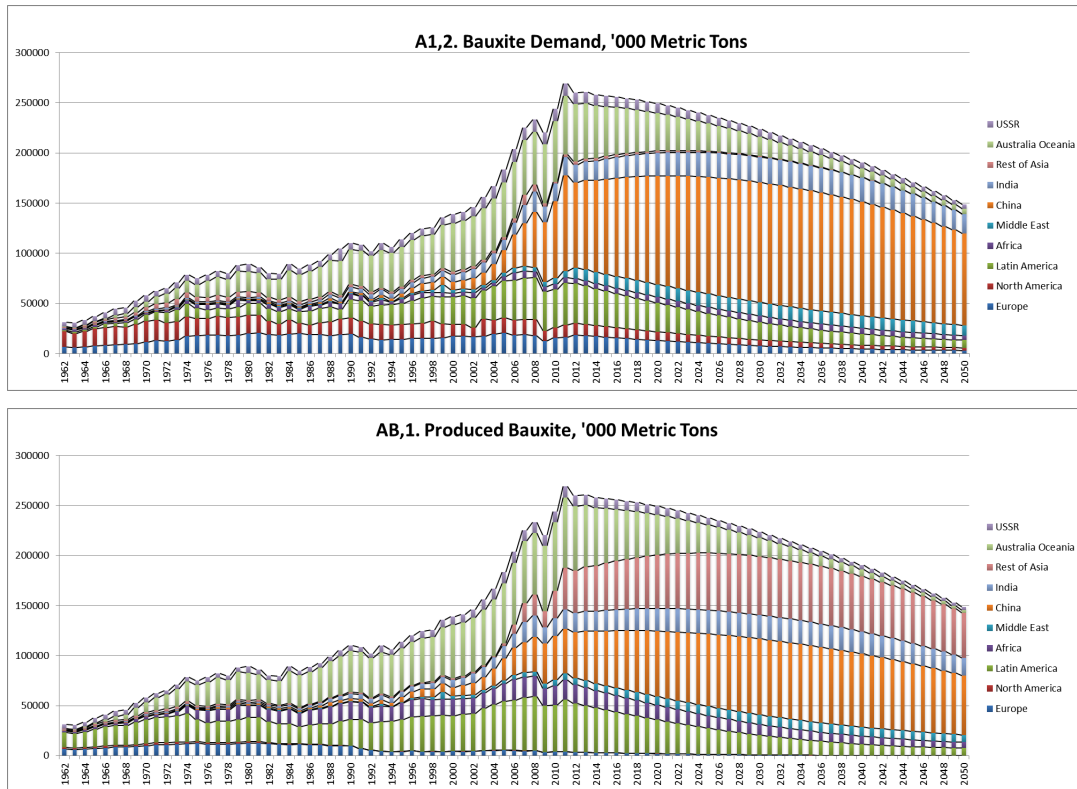


Figure 38 shows the alumina and bauxite demand and production as a result of the primary aluminium production levels in this scenario. The total alumina demand declines

from around 95 million metric tons in 2011 to 60 million metric tons in 2050, higher than the other scenarios due to the higher level of primary aluminium production. As China is the dominant producer of primary aluminium in this scenario, the majority of the alumina demand comes from China. As in the previous scenarios based on the assumptions made regarding alumina production, China is the dominant producer of alumina and thus has the greatest demand for bauxite, based on the assumptions made. The level of bauxite demand globally is around 260 million metric tons in 2011 to a little over 150 million metric tons in 2050. Once again as in the previous scenarios, to meet this bauxite demand Rest of Asia and China become the major producers of bauxite starting from around 2015 to 2050, gradually stealing share away from Australia and Oceania and Latin America.

Figure 38. Scenario 4: Alumina and Bauxite Demand and Production by Region from 1962-2050





In this way, the stock-driven, trade-linked, multi-regional model is able to answer the second strategic question, “How can future production of aluminium and fabrication of final products meet this demand?” The above results show how the stock-driven model can provide important insights for companies along the entire value chain of the global aluminium cycle and allow them to better understand the future of the aluminium industry by evaluating a set of alternatives and scenarios and making key assumptions.

3.3. Summary of Scenario Results

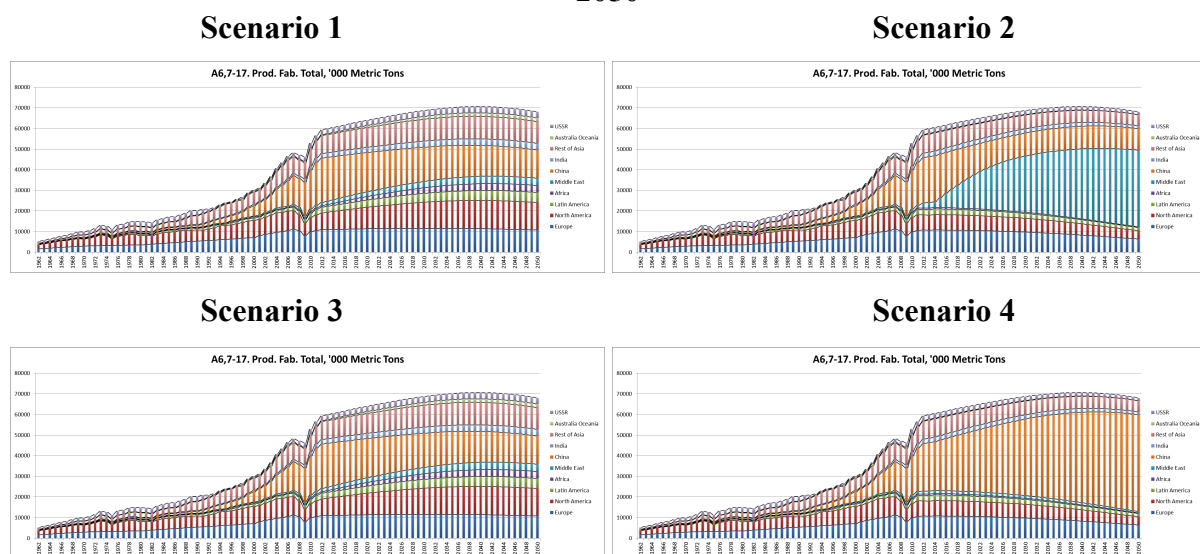
From the scenario results in section 3.1 and 3.2 and the answers to the key strategic questions posed in the introduction, companies across the aluminium cycle are able gain a better understanding of future flows of the global aluminium cycle given potential future alternatives. These results could provide valuable insights for strategy development within these companies and allow them to assess key opportunities and threats within the various regions around the world.

The results of the in-use stock scenario show that China is a key region for future aluminium consumption and product demand across the majority of product categories, and Rest of Asia is also expected to be an important region for certain product categories such as Auto & Light Truck, Packaging Cans, Consumer Durables, and Other. The regions with

strong historical demand for aluminium products, North America and Europe, continue to be key regions with significant levels of future demand for many product categories.

To meet this future level of aluminium consumption and demand, various regions play an important role depending on the scenario analysed. As figure 39 summarises, in scenarios 1 and 2, China and Rest of Asia are key regions for product fabrication companies, since the manufacturing of final products is to happen domestically within each region to meet demand in the future. These regions are also important for scrap dealers, since they will have increasing scrap outflows from 2012 to 2050. However, in scenarios 2 and 4, depending on which region is the dominant primary aluminium producer, either the Middle East or China will overwhelmingly be the most important for the manufacturing of final products by 2050. Thus, depending on which future alternatives are evaluated, product manufacturers are able to gain valuable insights into which regions they should be focusing on in the future.

Figure 39. Total Product Fabrication for All Product Categories by Region from 1962-2050



Based on the primary aluminium scenarios and assumptions analysed, summarized in figure 40, the dominant region will be a key strategic area for primary aluminium companies, depending on the whether the Middle East or China is dominant. However, in all scenarios, there is expected to be a significant decline in primary aluminium production by 2050, as recycled scrap becomes more abundant and available to satisfy aluminium demand, summarised in figure 41. This potentially has significant implications for aluminium companies who would benefit from investing more in their recycling and remelting businesses instead of primary aluminium production.

Figure 40. Primary Aluminium Production by Region from 1962-2050

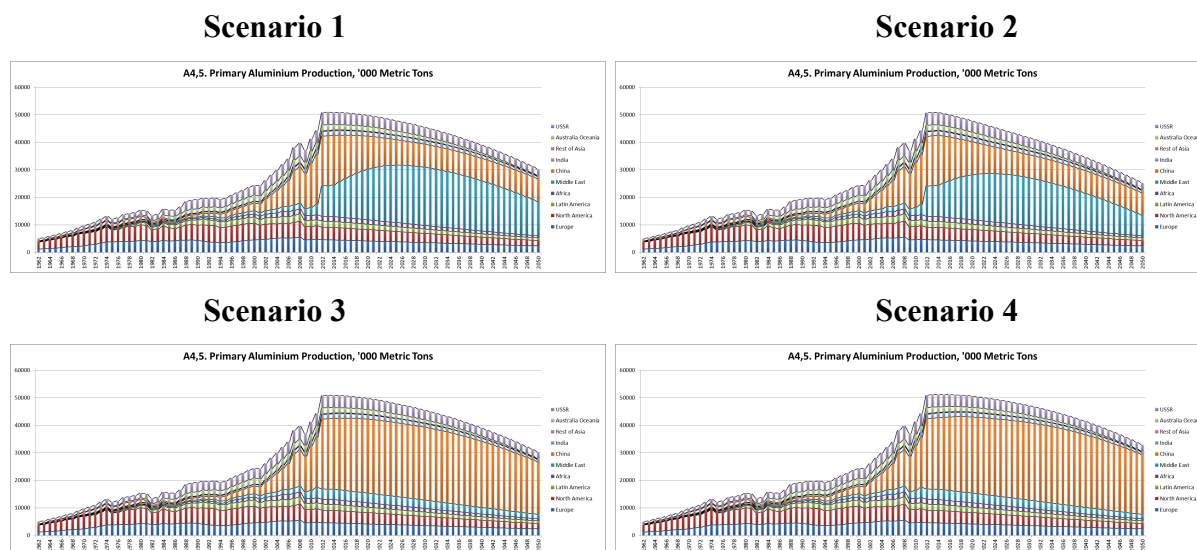
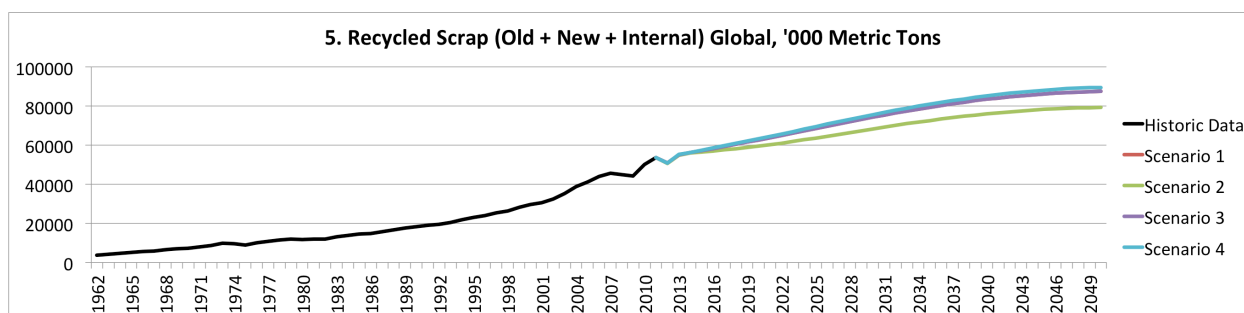


Figure 41. Global Recycled Scrap Available by Scenario from 1962-2050



As a result of the decline in primary aluminium production by 2050 across all scenarios, global levels of alumina and bauxite production are also expected to decline, summarised in figure 42. Based on the scenarios and assumptions defined, China is expected to be a key region for alumina production in the future, dominating alumina production by 2050. China and Rest of Asia are expected to make up the biggest share of bauxite production by 2050 based on the assumptions made. This is significant for the alumina and bauxite industry, as it could potentially indicate the need to pursue other uses for alumina and bauxite outside of aluminium production.

Figure 42. Global Alumina Production by Scenario from 1962-2050

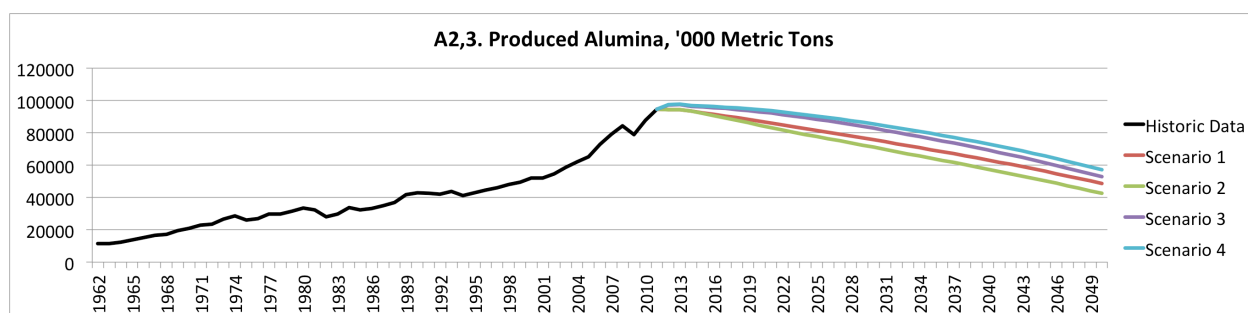
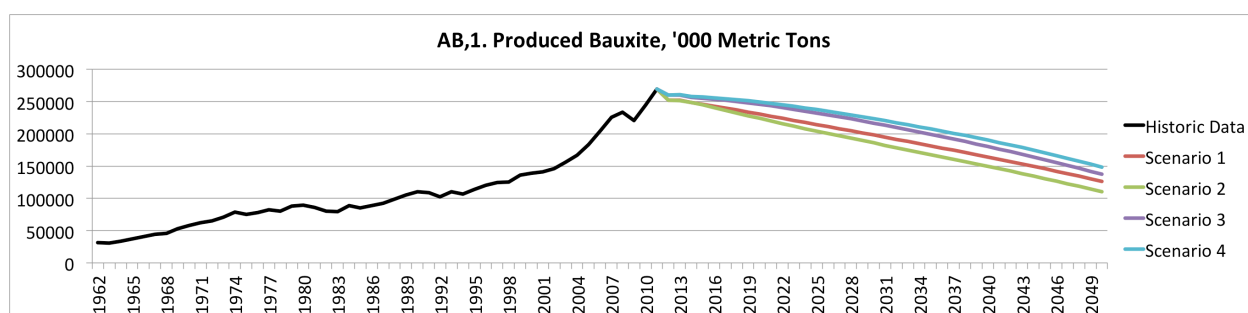


Figure 43. Global Bauxite Production by Scenario from 1962-2050



A very important consideration, as mentioned before, is that these results are entirely dependent on the specific assumptions and scenarios defined in section 2. What the results do show, however, is that the stock-driven model can be a powerful tool for scenario analysis and strategy development for companies in the aluminium industry. By defining and evaluating a concrete set of future scenarios and specified assumptions, the stock-driven model is able to provide answers to key strategic questions and allow the aluminium industry to gain valuable insights into the future of the global aluminium cycle for strategy development.

4. Further Discussion

In his paper on long-term forecasting, Spyros Makridakis mentions that:
“Long-term forecasting is difficult and challenging for two reasons. First, the long-term future is not simply an extrapolation of the past because of technological and other changes. Second, humans, in their attempt to profit from and influence what will happen, can and do change the course of future events to achieve desired goals.” (Makridakis, 1996).

The above statement is highly relevant for the scenarios and assumptions that were tested and highlighted using the stock-driven, trade-linked, multi-regional model in this paper. As described in section 2, the scenarios and assumptions used in the model were

primarily developed by determining trends from historical data and assuming that these trends will continue into the future using a defined growth functions and trendlines.

The scenario for future aluminium consumption based on historical trends is very conservative when compared to other scenarios developed to forecast aluminium in-use stock, as figure 5 shows, and it utilizes one very specific growth function, defined in equation 1, to forecast how aluminium consumption could evolve in the future. It is also based on a fixed set of assumptions regarding lifetimes of aluminium products, which may also change over time and are not accurately captured in either the historical data or the forecasted data. This is also true for the bauxite production, alumina production, and scrap treatment scenarios, which are based on defined trends using historical data as well as the specific negative square growth function to determine future regional distribution. Even the 4 specific scenarios defined for primary aluminium production and product fabrication are developed through understanding historical trends, and they capture only a subset of potential future alternatives that can be analysed through the stock-driven model. Thus, all of the results from the model described in section 3 are built upon a predetermined set of alternatives that were extrapolated from historical data in order to answer the key strategic questions posed.

Moreover, the data determined through the historical models (Ramkumar, 2013) could be further refined and improved. The historic data is based on assumptions from the GARC (2011) model as well as various extrapolations that still have a lot of data gaps and are not robust. Currently, the International Aluminium Institute is working to address these data issues in cooperation with each of the regional aluminium associations in an effort to have more detailed model assumptions and more accurate data for the historical, trade-linked, multi-regional models. These updates could significantly impact the scenarios and assumptions made in this paper and thus affect the results in the stock-driven model.

As Makridakis states and as was briefly mentioned in section 2, any number of technological changes, human influences, government policies, or other factors could affect the future development of the aluminium cycle. The scenarios defined in this paper may not necessarily reflect plausible alternatives for the future of the aluminium industry, as they are based solely on historical trends and specific assumptions that may ignore many of these other factors. But, these additional considerations and factors can be easily incorporated into the model to create better scenarios that are more relevant and important to the aluminium industry. Various growth alternatives for future aluminium consumption and demand, more concrete scenarios for primary aluminium production and product fabrication, and additional

scenarios for bauxite, alumina, and scrap can be developed that try to account for factors such as potential government policies, changes in consumer behaviour, new technologies, etc.

The aim of this paper is not to accurately forecast future aluminium flows to 2050. Rather, as mentioned in the introduction, the goal of this research effort is to develop a stock-driven, trade-linked, multi-regional model and use the model to test defined example scenarios to answer specific strategic questions important to understanding the future of the aluminium industry. In this way, this paper aims to use these results to illustrate how the stock-driven model can be a robust tool for analysing scenarios for how the global aluminium cycle can evolve and can provide insights for developing long-term business strategies for companies along the aluminium value chain.

In the future, the stock-driven, trade-linked, multi-regional model could be further expanded to incorporate greater detail and include various additional layers - energy, process technology, quality of aluminium flows, financial market mechanisms, and many others. These additions would greatly expand the stock-driven model's ability to test more complex scenarios, allowing the model to provide deeper insights for strategy development. Companies along the entire value chain of the global aluminium cycle - from bauxite mining companies, alumina producers, primary aluminium producers, product fabrication firms, to scrap dealers - can use such a tool to test various future scenarios and develop appropriate business strategies that will enable them to more effectively respond to future opportunities and threats.

References

- Bertram, M., Martchek, K. J., & Rombach, G. (2009). Material flow analysis in the aluminum industry. *Journal of Industrial Ecology*, 13(5), 650-654.
- Bradfield, R., Wright, G., Burt, G., Cairns, G., & Van Der Heijden, K. (2005). The origins and evolution of scenario techniques in long range business planning. *Futures*, 37(8), 795-812.
- Chen, W. Q., & Shi, L. (2012). Analysis of aluminum stocks and flows in mainland China from 1950 to 2009: Exploring the dynamics driving the rapid increase in China's aluminum production. *Resources, Conservation and Recycling*, 65, 18-28.
- GeniSim. (Accessed 2014). <http://www.genisim.qc.ca/download/smelters-with%202014%20projection.xls>
- GARC. (2011). Global Aluminium Recycling Model. London: Global Aluminium Recycling Committee, International Aluminium Institute.
- Hatayama, H., Daigo, I., Matsuno, Y., & Adachi, Y. (2009). Assessment of the recycling potential of aluminum in Japan, the United States, Europe and China. *Materials transactions*, 50(3), 650-656.
- Liu, G. (2013). *Rolling Out the Anthropogenic Aluminum Cycle: With Foci on Temporal, Geographical, and Emission Perspectives* (Doctoral dissertation, Norwegian University of Science and Technology).
- Liu, G., Bangs, C. E., & Mueller, D. B. (2011). Unearthing potentials for decarbonizing the US aluminum cycle. *Environmental science & technology*, 45(22), 9515-9522.
- Liu, G., Bangs, C. E., & Mueller, D. B. (2013). Stock dynamics and emission pathways of the global aluminium cycle. *Nature Climate Change*, 3(4), 338-342.
- Liu, G., & Mueller, D. B. (2012). Addressing sustainability in the aluminum industry: a critical review of life cycle assessments. *Journal of Cleaner Production*, 35, 108-117.
- Luo, Z., & Soria, A. (2007). Prospective study of the world aluminium industry. *JRC Scientific and Technical Reports. EUR*, 22951.
- Makridakis, S. (1996). Forecasting: its role and value for planning and strategy. *International Journal of Forecasting*, 12(4), 513-537.
- Menzie, W. D. (2010). The global flow of aluminum from 2006 through 2025. US Department of the Interior, US Geological Survey.
- Pauliuk, S., Milford, R. L., Müller, D. B., & Allwood, J. M. (2013). The steel scrap age. *Environmental science & technology*, 47(7), 3448-3454.
- Pawlek, R. P. (2012). Primary Aluminum Smelters of the World. *Light Metal Age*. http://www.lightmetalage.com/producers_primary.php

Ramkumar, S. (2013). Historical, Trade-Linked, Multi-Regional Models of the Global Aluminium Cycle. Unpublished thesis paper.

UN. (2013). United Nations, Department of Economic and Social Affairs, Population Division World Population Prospects: The 2012 Revision, DVD Edition.

UNCTAD. (2000). Recent and planned changes in production capacity for bauxite, alumina and aluminium. <http://unctad.org/en/docs/poitcdcomd27.en.pdf>

USGS. (2009). Bauxite and Alumina. *Mineral Commodity Summaries, January 2009*. <http://minerals.usgs.gov/minerals/pubs/commodity/bauxite/mcs-2009-bauxi.pdf>