Human Systems Management 34 (2015) 237–248
DOI 10.3233/HSM-130851
IOS Press

Systems perspective of the primary aluminum supply chain: Unintended consequences of participant policies

David L. Olson*
College of Business Administration, University of Nebraska, Lincoln, NE, USA

Abstract. Supply chains have been proposed as complex adaptive systems. This paper looks at the global aluminum supply chain network in those terms. Developments in this industry have included formation of a cartel by bauxite producing countries, emergence of Australia as a leading producer, the collapse of communism in Europe, and the rise of Chinese production in all phases of primary aluminum production. Complex adaptive systems literature is reviewed, and the world aluminum production system described. This includes identification of system elements, their relationships, interactions, and developments. Analysis in terms of how this production system exhibits complex adaptive systemic behavior across the supply chain is provided. The decentralized behavior of the overall primary aluminum system provides understanding of how individual agents, be they multinational firms, individual governments, or cartels are unable to totally control the system in the long run.

Keywords: Supply chains, complex adaptive systems, primary aluminum, global systems

David L. Olson is the James & H.K. Stuart Professor in MIS and Chancellor's Professor at the University of Nebraska. He has published research in over 150 refereed journal articles, primarily on the topic of multiple objective decision-making and information technology. He has authored 20 books. He has made over 150 presentations at international and national conferences on research topics. He is a member of the Decision Sciences Institute, the Institute for Operations Research and Management Sciences, and the Multiple Criteria Decision Making Society. He was a Lowry Mays endowed Professor at Texas A&M University from 1999 to 2001. He was named the Raymond E. Miles Distinguished Scholar award for 2002, and was a James C. and Rhonda Seacrest Fellow from 2005 to 2006. He was named Best Enterprise Information Systems Educator by IFIP in 2006. He is a Fellow of the Decision Sciences Institute.

1. Introduction

Supply chains have become critically important elements of global business. The study of supply chain management unites procurement, operations and distribution into a unified discipline [1]. Supply chain networks involve high levels of interdependence [2]. The idea was important to military operations throughout human history, was critical in vertically integrated industries during the industrial revolution, and continues in today's more open economic structure. Supply chains also are important in other human efforts, to include disaster relief [3].

Supply chains have been suggested to be complex adaptive systems [4, 5]. Contemporary global business has seen the passing of vertical integration (for many sectors anyway), replaced by supply chains of cooperating but at least quasi-independent entities. Supply chains usually emerge rather than result from the purposeful design of a single controlling entity [6]. McCarthy et al. [7] and Choi et al. [8] applied the concept of complex adaptive systems to core manufacturing firms within supply chains. The paradigm of

*Corresponding author: David L. Olson, James & H.K. Stuart Professor, College of Business Administration, University of Nebraska, Lincoln, NE 68588-0491, USA. Tel.: +1 402 472 4521; Fax: +1 402 472 5855; E-mail: dolson3@unl.edu.

complex adaptive systems for supply chains is useful in that it explains how unanticipated emergence often is observed. The ability of supply chains to adapt in this complex, dynamic, and interdependent environment has been labeled resilience [9]. This paper presents the global primary aluminum industry viewed from the perspective of complex adaptive systems.

2. Literature review

Viewing supply chains as adaptive systems has provided insight in a number of studies. Closs et al. [10] used a socio-technical systems theoretical perspective to view how organizations cope with product complexity. Parmigiani and Rivera-Santos [11] looked at how multinational corporations could resolve system voids in product, labor, and capital markets, to include addressing regulatory ambiguities and missing contracting mechanisms often found in supply chain sourcing. Information systems have been cited as a means for manufacturing components of supply chains to improve business performance through electronic collaboration [12] and have been proposed as tools for supply chains to assimilate innovation [13]. Systems perspectives also provide a perspective with which the sustainability of supply chains can be assessed [14].

2.1. Supply chain systems

Systemic aspects of supply chains arise inherently because they are collections of independent agents, unlike vertical hierarchies. While vertical integration was considered appropriate during the industrial revolution and gilded age (see Standard Oil, US Steel, Alcoa) probably because their investors wanted to fully control their markets as well as extract every cent of profit, vertical hierarchy inevitably leads to some elements of the chain being relatively inefficient.

Aluminum is a major product in global business, a key component of products from beverage cans to airplanes. The history of the aluminum industry is quite interesting [15], evolving in a shifting locus centered in Europe in the 19th Century, North America in the first part of the 20th, and continued evolution today toward Australia, Brazil, and China [16]. The aluminum industry is a complex system that has adapted to change due first to exhaustion of raw inputs, but also to a number of political factors such as World War II, and associations of producing nations in the past 50 years, as well as links to the availability of inexpensive energy.

2.2. Systems theory and supply chains

Systems theory is a well-developed field [17], extending ideas often originally arising from sciences, but providing many valuable concepts useful in business [18] and social systems [19]. Holland [20] studied adaptation in systems. Senge [21] was an early proponent of systems theory in learning organizations. Gharajedaghi [22] considered the value of systems thinking in complex and chaotic domains.

There are a number of systems concepts that are appropriate to supply chains. First is the idea of system organization. Williamson [23] argued that uncertain, frequent, transaction-oriented business calls for organizations. There are two extreme types: markets work well with straightforward exchanges, but involve high levels of uncertainty. Hierarchies provide means to cope with bounded rationality and opportunism to cope with this uncertainty, but introduce inefficiencies. Powell [24] viewed networks of organizations as means to gain the efficiency of markets in today's global business environment.

Complex adaptive systems are viewed as having a life of their own [25], which they labelled autopoeisis. Autopoietic systems are capable of creating and maintaining themselves. While Maturana and Varela were interested in living cells, the ideas apply to sociological systems as well. Supply chains certainly fall into that realm, as they often consist of independent agents that might participate in all parts of a supply chain in a temporary sense, with new sources entering through market competition. Thus instead of John D. Rockefeller forging a rigid hierarchical Standard Oil Trust, a more efficient (and more chaotic) free market might arise. Complex adaptive systems are thus said to exhibit emergent behavior [26].

The butterfly effect is used to visualize the phenomenon of emergence within complex systems. The butterfly effect refers to the concept that the flapping of a butterfly's wings half a world away could lead to magnification in the weather system resulting in a hurricane across the globe. This implies that phenomena emerge from a collection of interacting objects in a complex, nonlinear fashion evading precise modeling [27]. System development is viewed as one-way, or irreversible [28]. System elements interact through feedback. The hope is that understanding object relationships can lead to understanding at the macro-level, and might lead to better prediction and control (although nonlinearities often make precise modeling impossible).

3. Complex adaptive systems

This document seeks to view this industry as a complex adaptive system (CAS). That perspective looks at behaviors and effects of system elements to include evolution of the system over time, with self-organization when faced with threatening change. The CAS view looks at intertwined relationships among system elements, sometimes cooperative, sometimes competitive. CAS views system components below:

- Elements – agents, with different degrees of autonomy, interactions, and learning.
- Behaviors – co-evolution and self-organization when faced with challenges.
- Effects – adaption that is often non-linear and/or irreversible.

Supply networks are very important to contemporary global business. Practically every product marketed today is delivered to customers via some supply chain. Table 1 shows Holland's [29] characteristics of supply network elements:

CAS supply networks can exhibit behaviors such as self-organization. They are often characterized as operating on the edge of chaos, with structures emerging in response to a changing environment. A common supply chain behavior is the bullwhip effect, with inventories exploding in various parts of the supply chain due to rapid changes in demand that induce reactive response.

We will seek to evaluate how the global aluminum production system has exhibited some of these features.

Table 1
Supply chain network systemic features

Elements	Components	References
Agents	Actors – suppliers, manufacturers, retailers, customers Partnerships & alliances	Wycisk et al. [30] Choi et al. [8]
Interaction	Resources & activities Resource exchange (finance, information, knowledge)	Hakansson and Snehota [31] Wycisk et al. [30]
Autonomy	Relative degree of independence of operation	Wycisk et al. [30]
Learning	Knowledge exchange & development	Dagnino et al. [32]

4. The aluminum industry

The aluminum production system consists of mining bauxite, refining bauxite into aluminum oxide (alumina), and smelting alumina into aluminum. The production facilities are thus bauxite mines, alumina refineries, and aluminum smelters. Bauxite is a very common mineral found practically everywhere, but in highly variable levels of quality (as measured in the amount of ore needed to obtain a ton of alumina). Bauxite mines are usually strip mines, and bauxite mining is often deleterious to the environment. Alumina refining is capital intensive, and since the volume of ore required to obtain a ton of alumina is high, refineries have a tendency to be found close to mines to cut transportation costs. However, mines are often found in places with low levels of infrastructure, so it is not always the case that refineries are co-located with mines. It may take 2.6 tons of bauxite to generate a ton of alumina, with the ratio varying significantly by location. The next stage of production is smelting, where a more consistent ratio of 1.93 tons of alumina to generate a ton of primary aluminum. Primary aluminum is then passed on to producers of aluminum materials, be they cans, siding, automobiles, planes, etc. There is a secondary market for aluminum (recycling). However, this volume is not nearly on the same scale as the primary aluminum market.

4.1. History

Aluminum production on a large scale began in Europe, with Pechiney (a French firm) being a pioneer in the 19th Century. A common occurrence has been that the viable bauxite deposits (in terms of economic feasibility) are depleted over time. Thus French and other European sources of bauxite were to a degree depleted, and the bulk of production moved on to North America. Alcoa in the United States was a major producer in the 20th Century, but US deposits of bauxite were soon depleted in turn (with Arkansas mining lasting until the 1990s). Alcan in Canada spun off from Alcoa, but Canadian bauxite also was exhausted for the most part. Pechiney, Alcoa, and Alcan then obtained rights to Caribbean sources in the 1960s, with especially rich deposits in Jamaica, Surinam, and Guyana.

As former colonies grew independent after World War II, they often reviewed prior arrangements with developing firms such as Pechiney, Alcoa, and Alcan, seeking what they perceived to be fairer sharing of proceeds. In the 1970s, inspired by OPEC, Jamaica was a driver in the formation of the International Bauxite Association (IBA), organizing bauxite producing nations into a cartel to counter what they saw as unfair accounting and pricing controlled by the producing firms. Australia at that time had a liberal national government, which committed Australia to join the IBA. However, Australian bauxite mines, which had a relatively low quality, were located in provinces controlled by conservatives, who opposed the IBA in principle. Ensuing events found an interesting shift in production away from the more militant IBA members in the Caribbean to Australia.

We now review some statistics relating to the primary aluminum industry, based on annual reports of the United States Coast and Geodetic Survey's Mineral Industries relating to Bauxite and Alumina and on Aluminum.

4.2. Demand

The demand for aluminum follows world economic output. Figure 1 shows a fairly steady increase in demand for primary aluminum, with notable recessionary periods in the early 1980s, the early 1990s, the dot-com bubble of 2001, and the real estate bubble period around 2008.

4.3. Price

The price of aluminum was quite stable (essentially set by the oligopoly of producing firms) until the IBA was created in the mid-1970s. After that, you can see that the price of aluminum has been highly volatile. Figure 2 provides a long-range view of this price.

There was a slight drop in price in 1973 with the recession induced by OPEC. But by 1980, the price had risen to almost 80 cents per pound. The recession of the

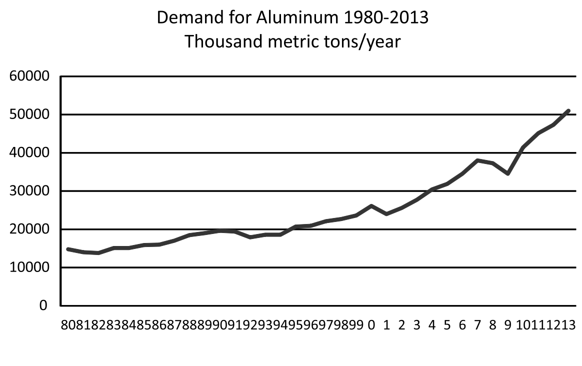

Fig. 1. Primary Aluminum Demand 1980–2013.

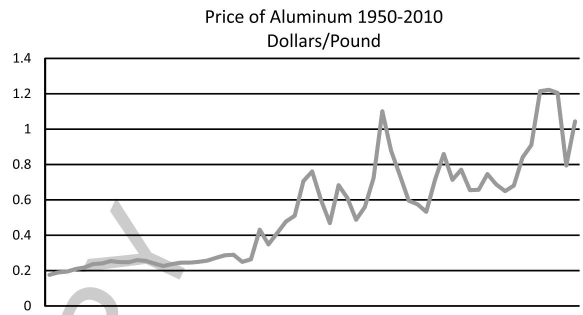

Fig. 2. Long range price in aluminum from 1950–2010.

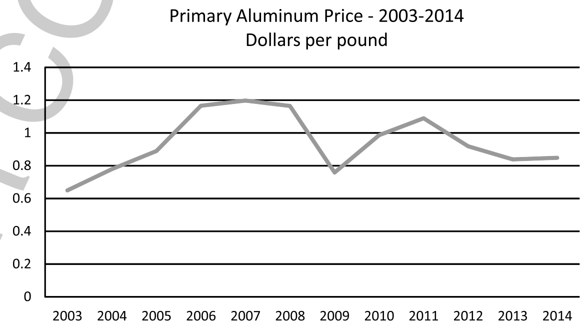

Fig. 3. Price of Primary Aluminum 2003–2014.

early 1980s led to declines in demand, but by 1990 a peak over $1 per pound was reached. This was followed by a crash back to below 60 cents per pound, finally recovering in the early 2000s, until the recession of 2008 when the price again plummeted. An easier to follow graph of more recent prices shows that recessionary drop with subsequent recoveries peaking in 2011, and then tailing off to just above 80 cents per pound. Figure 3 looks more closely at recent changes in aluminum price averages per year.

Figure 3 shows the impact of reduced economic activity after the real estate bubble burst in 2008. By 2011, things recovered, but have been fairly stagnant (and declining) since.

4.4. Bauxite production trends

We have categorized bauxite producing countries by category. The international bauxite association (IBA) has continued to provide the bulk of bauxite produced, but the BRIC countries are catching them. This is especially true for China. Centralized countries (excluding Russia, which is part of BRIC) and European countries are dropping out as significant players. As shown

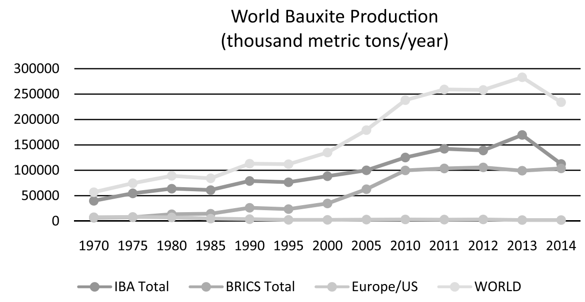

Fig. 4. Bauxite Production by Year.

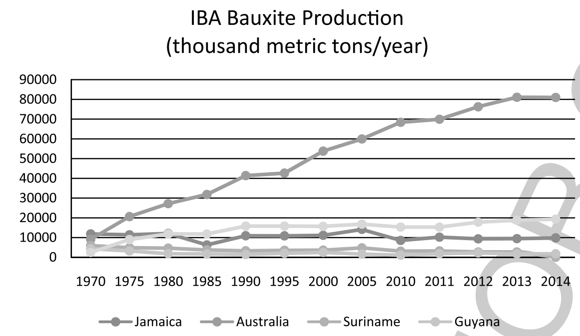

Fig. 5. IBA Bauxite Production per year.

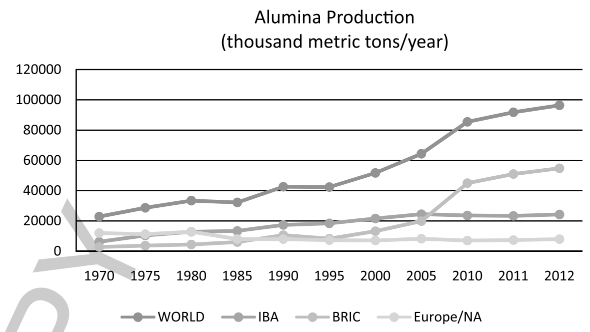

Fig. 6. Alumina Production by Sector.

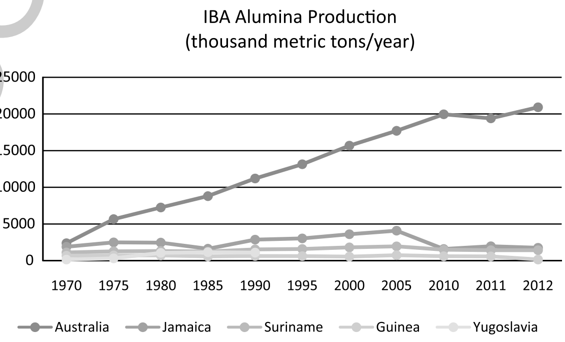

Fig. 7. Alumina Production by Year within IBA.

in Fig. 4, Australia soon took over dominance in the production of bauxite during the 1980s, replacing Caribbean countries. In the 2000s, China and Brazil have become major contenders as well.

Figure 5 shows the trends for the five leading IBA bauxite producers. Three of these were Caribbean IBA stalwarts (Jamaica, Suriname, and Guyana). Guinea has rich deposits in Africa, which have been directed to Europe at least in part.

Bauxite production figures in the Appendix show more clearly Australia's dominance within IBA, as well as the growth in each BRIC country. It can be seen that Australian production rapidly took off in the 1970s, and has continued that upward trend while the other major IBA producers have seen relatively flat (if not declining) production. We contend that this is due to systemic response on the part of industry firms to shift production to the more politically favorable Australian sources.

4.5. Alumina

Alumina production has been steady, in part because of the high capital expenditure required to build refineries. However, in the 200s China has pulled ahead to become the highest volume producer of alumina. Figure 6 shows sector production of alumina refining by year.

Figure 6 shows that alumina production has seen upward growth in total. But this growth is occurring more in BRIC countries (especially China), while IBA and developed economies have had flat growth trends. The Appendix production figures for alumina show that within the IBA, only Australia has had consistent growth. All of the BRIC countries have higher production.

Figure 7 displays alumina production within the IBA.

Australia has obviously seen the bulk of growth in production. Yugoslavia was a promising alumina producer until its dismemberment in the early 1990s. The other three major IBA producers have had steady (in the case of Surinam) to declining production (for Jamaica and Guinea).

4.6. Aluminum

Production of aluminum requires high volumes of electricity. A number of countries have energy

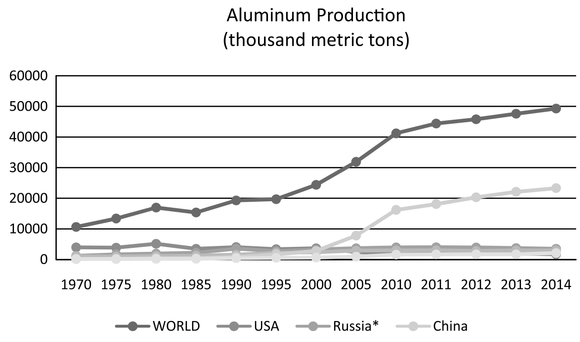

Fig. 8. Alumina Production by Year.

sources enabling them to participate at a high volume. The Canadian government created large hydroelectric capacity in British Columbia, enabling it to become a major producer. Interesting new entrants into this field are the United Arab Republic (mostly Dubai) relying on the use of flare gas from oil production, and Iceland, relying on thermal energy. But Fig. 8 shows that China has again become the producer with the greatest growth in the past ten years.

World smelting of aluminum has trended upward over the period of analysis, with temporary declines in response to recessionary periods. Figure 8 shows, however, that the bulk of growth since 2000 has been in China. The Appendix figures for aluminum show the US production way down, that for China way up. New smelting has occurred in Dubai, Saudi Arabia, Qatar, and Mozambique.

4.7. Trade networks

The networks of trade are primarily expected to be determined by economics, complicated by the inertia imposed by high capital costs for refineries and the availability of massive quantities of energy required by smelting. In the 1970s, the trade between the Caribbean and the US was very strong. As we have discussed, this has changed to some degree. Liu and Műller [33] provided material flow analysis of the aluminum industry. They state that currently the Southern hemisphere is the main primary resource supplier, while production and consumption are found concentrated in the Northern hemisphere. Their data in 2008 showed that Australia, Brazil, Indonesia, Jamaica and Guinea were the leading net exporters or resources, with Russia, Spain, Canada and Norway centers of production and the US, China, and Japan the biggest net importers. Germany had high levels of activity in both production and consumption (as did China).

As to trade routes, Australia was a heavy shipper to China and Japan, but also sent products to refineries in the Middle East and to the US. China exported primary aluminum around the world, but consumed the majority of its output. Guinea shipped bauxite to Europe for the most part. Brazil serviced both the US and Europe. Caribbean sites shipped to different sites, to include Guyana connections to Russia. China was seen to stand out in its growth to count for nearly a quarter of the global total, to include nearly half of primary aluminum production.

5. The aluminum CAS

The aluminum system can be better understood by viewing the relationship of production facilities.

5.1. The primary aluminum system

Integration across the primary aluminum supply chain has varied. Guyana has become solely a bauxite exporter. Jamaica and Guinea have evolved into exporters of refined alumina. Suriname and Australia have the complete production facilities through smelting. Within BRICS, most have the full supply chain capabilities, with the exception of South Africa which needs to import alumina for its smelters. The declining sector of Europe and North America see some change. Greece and Spain have facilities in all three production types. Canada imports bauxite, as do Ireland and Japan. Ireland exports bauxite to smelter, including places like Iceland and Norway. Japan used imported bauxite (from Australia) to refine and smelt.

Before the 1970s, the aluminum industry was dominated by firms, just as most industry was from the dawn of the industrial revolution. Massive amounts of capital were needed for construction of production facilities (refineries and smelters) utilizing breakthroughs in technology. Pechiney in France, Alusuisse in Switzerland, and Alcoa in the United States developed vertical monopolies. The demand for aluminum skyrocketed with World War II. In the United States, the Federal Government took action to assure supply of war materiel by taking some of Alcoa's facilities and creating others, enabling the entry of other firms such as Kaiser into the market.

The nature of bauxite deposits led to their depletion, first in Europe, then in the US, leading to efforts to find new sources. The most economical new sources (in terms of processing differences due to quality of ore, as well as shipping) led to identification of attractive deposits in Jamaica, Guyana, and Suriname, as well as in Guinea. Massive (although not as high quality) ores were found in two dispersed areas of Australia as well.

The formation of the International Bauxite Association in 1974 (led by Jamaican Prime Minister Michael Manley) disrupted the vertically integrated industry. Caribbean IBA members renegotiated arrangements with aluminum firms. In Jamaica's case, they obtained controlling interest (51 percent) of Kaiser facilities, Suriname allowed continued firm ownership but wrested decision making control, while Guyana relied on expropriation. Meanwhile, Australia, which had opened some highly productive mines, elected a highly liberal national government under Don Dunstan, who viewed the IBA very favorably. This was balanced by provincial conservative politics, which were quite favorable to Alcoa and aluminum development firms. Thus while Australia was a part of IBA, they operated quite independently. Australia has the full spectrum of production, although their limited energy supply makes them a minor smelter (as is Surinam).

A major change is the shift of demand to BRIC countries. All four (all five if you make it BRICS) are involved in the aluminum industry. The fifth, South Africa, is only involved in smelting. But China has surged to the top in all phases of the industry, while Brazil and India also have demonstrated impressive growth. Venezuela is also an integrated participant in all phases of the industry. Meanwhile, in Europe, Ireland and Spain have appeared as alumina refiners, while Norway and Iceland utilize some of their spare energy to smelt aluminum. In the Middle East, Iranian production levels are still relatively small. More interesting is development of smelting in oil-rich countries.

5.2. *Primary aluminum as a complex adaptive system*

Complex systems is an interdisciplinary field seeking to explain how numbers of relatively simple entities organize into collective evolving wholes without the benefit of a central controller [34]. Complex adaptive systems are more than the sum of their parts, exhibiting adaptive, dynamic, goal-seeking, self-preserving, evolutionary behavior. Choi et al. [8] provided a framework for adaptive supply chain networks (Table 2):

Agents are the participants in a system. In the aluminum production system, these include producing firms, host countries, and customers. Agency is defined as the ability to meaningfully intervene in response to events. Firms used to operate as local monopolies or an oligopoly, setting prices and royalty rates as they chose. Host countries in the 1970s formed the

Table 2
Complex adaptive system elements of supply chains

Elements	CAS	Descriptions
Internal Mechanism	Agents	Agents share interpretive and behavioral rules
	Self-organization & emergence	Patterns created through simultaneous and parallel actions Extensive inter-relationships possible
	Connectivity	Extensive inter-relationships possible
	Dimensionality	Negative feedback and controls reduce dimensionality Autonomy and decentralization increase dimensionality
Environment	Dynamism	Changes constant and inter-dependent
	Rugged landscape	Global optimization simple if criteria independent Complex if criteria inter-dependent
Co-Evolution	Quasi-equilibrium & state change	Attractors sensitive to change with variance from equilibrium
	Non-linear change	Lack of linear correlation between cause and effect
	Non-random future	Common patterns of behavior observable

International Bauxite Association to enable them to control events. Jamaica obtained 51 percent of Kaiser's facilities, and smaller proportions of other producer operations, while imposing a levy that has evolved into a tax. Guyana nationalized production facilities, while Suriname relied on taxation. Australian provincial governments had a pro-business policy, which led to international firms feeling much more comfortable in shifting production in the direction of Australia despite what had been considered an inferior ore quality.

Self-organization and emergence arise in complex adaptive systems due to simultaneous and parallel actions of agents. Emergence is the arising of new, unexpected structures, patterns, properties, or processes. In the aluminum production system, the formation of the IBA can be viewed as an inducement to increased production in Australia, with actual reduction of production in the more militant IBA countries such as Jamaica, Guyana, and Suriname. Another emerging change has been the rapid development of all phases of the primary aluminum sector in China. Co-evolution is an important CAS concept [18].

The level of connectivity in a network is a factor in network complexity. Because It is not frangible, capital intensive refineries tend to be tied to mine sites. Jamaica, Guyana, and Suriname took actions to gain pricing and operational control away from the firms that had operated pretty much as they pleased up until 1970. The independent action of Australia within the IBA led to the ineffectiveness of that cartel. New refineries have developed in places such as Ireland and Spain that have good sea-lane linkages to smelting sites with low-cost energy such as Iceland and Norway. Alumina is more frangible, making isolated locations with low-cost energy such as the Middle East viable locations for new smelters.

Dimensionality of a complex adaptive system is defined as the degrees of freedom that individual agents have. Controls act as negative feedback to reduce dimensionality, while rules and regulations ensure constraint on individual agent behavior. The IBA was unable to successfully impose constraint on industry growth in Australia as opposed to expected growth in the Caribbean. Confiscatory policies in Jamaica, Guyana, and Suriname can be seen to have backfired, enabling new linkages in the Pacific.

A system's environment consists of external agents and their interconnections. In the primary aluminum sector, this can be seen to be customer and non-IBA government response. The demand for aluminum was strong in the 1970s, but declined with the economy in the 1980s. The dynamism involved changes in agent connections as demand for primary aluminum ebbed and ultimately expanded in the 1990s. During waning demand periods, alternative sources soon took over for the three Caribbean bauxite producers mentioned, with all of their bauxite production declining after 2008 while that of Australia and China continue to grow and Brazilian and Indian production levels seem relatively stable. There also was major upheaval in formerly communist countries. The USSR and Yugoslavia were major players in the industry. The succeeding states continue to be involved, but under a number of new state entities. This change in environment represents the rugged landscapes attributed to complex adaptive systems.

Co-evolution involves feedback through cooperation or resistance among agents. In the primary aluminum production sector, new balances arose resulting in quasi-equilibrium and state change. Bauxite production in 1990 was radically different than that of 1970, with Jamaica, Guyana, and Suriname still producing, but at the same or lower levels than in 1970, while massive increases have been seen in Australia, Guinea, Brazil, and India. In the alumina sector, the USA was the leading producer in 1970, but in 2012 had had about 60 percent of the 1970 production level while China has surged to nearly double the next highest producer (Australia). In primary aluminum production China is again forging to the top.

Non-linear change has been demonstrated in the unintended consequences occurring for Jamaica, Guyana, and Suriname. While there is no objective proof, it very much appears that industry response to the governmental actions of those countries has led to limited maintenance of activity in those countries and massive shift to Australia, China, India, and Brazil. A lot of this change of course is due to the emergence of China as a massive producer of practically all goods in the past 20 years. But some of the other change can be attributed to non-linear consequences.

The primary aluminum sector certainly demonstrates non-random future. New alumina entrants in Ireland and Spain as well as aluminum growth in the Middle East represent a pattern of emergence that the IBA members had not anticipated.

5.3. Systemic features of the primary aluminum system

Taking this framework, we apply it to the example of the global aluminum industry (Table 3).

Table 3
Linkage of complex adaptive system elements and the aluminum production system

Elements	CAS	Aluminum system
Internal Mechanism	Agents	Customers
		Firms (seek to control supply chain)
		Host countries (set tariffs; implement energy policy)
		International Bauxite Association (seek to set price)
	Self-organization & emergence	Response of Jamaica, Guyana, Surinam
		Australian response
		China
	Connectivity	Degree of coordination
		Independent action of Australia
		Firms become subordinate to host governments
	Dimensionality	Rule enforcement within IBA
Environment	Dynamism	Market – demand/price
		Emergence of China
		Collapse of Yugoslavia, USSR
	Rugged landscape	IBA difficulty in anticipating consequences of formation
Co-Evolution	Quasi-equilibrium & state change	New balances:
		Australian, Guinean bauxite
		Chinese in all three sectors
	Non-linear change	IBA action in 1974 Chinese growth in 2000s
	Non-random future	New alumina entrants (Ireland, Spain)
		New aluminum entrants (Iceland, Bahrain)

6. Conclusions

Marchi et al. [35] proposed an analytical framework for understanding supply chains as complex adaptive systems. They proposed the following strategies that might enable supply chains to cope with the turbulence and disruptions that occur in chaotic environments:

1. Promotion of interactions – linking upstream and downstream elements of a supply chain in a closer manner.
2. Encouraging autonomy – enabling flexibility in supplier relationships, supported by information and knowledge exchange.
3. Encouraging learning – seeking improved responsiveness to change and competitive advantages.
4. Recognizing creative space – learning and creating novelty leading to new market opportunities and technologies.
5. Developing capabilities to guide emergent effects positively – changes are sometimes negative, and supply chain management needs to identify and develop capacities to steer change to a positive direction.

The global primary aluminum industry saw a number of key events over the period 1970–2000.

- The International Bauxite Association was formed in the early 1970s.
- In the 1980s Australian mining interests operated in competition with rather than in cooperation with the IBA, gaining a large market share.
- In the late 1980s the Chinese government encouraged free market development.
- In 1990 communism for the most part was replaced with new freer market economies.

These events represent major changes in the world aluminum industry domain. Formation of the IBA made governments a major player in the primary aluminum industry, wresting some control from the firms that had dominated a formerly vertically integrated industry. Australian development swung the weight of control back away from the IBA, with Australian mines feeding its own refineries as well as those of Japan and China. China continues to develop new bauxite deposits and has become independent as a producer, increasing its production to a massive scale and emerging as a major exporter. Formerly communist countries in Europe meanwhile have seen major decreases (especially Yugoslavia) and adjustment (in Russia and the formerly Soviet states involved in aluminum).

A number of systemic features are observed. The interconnections of agents have seen a great deal of shifting alliances and cooperation. Bauxite production appeared to be dominated by the Caribbean in the 1970s. The 1980s saw Australian production boom. The 1990s and 2000s have seen China emerge as the leading producer. The downstream supply elements of alumina refining and aluminum smelting are following that trend. Additionally, new alumina facilities have grown in Ireland and Spain, on shipping routes to smelting facilities using energy available in Iceland and Norway. Meanwhile, the excess energy from petroleum in the Middle East is being harnessed to smelt aluminum in Saudi Arabia, the UAR, Dubai, Iran, and other Gulf States.

The butterfly effect of systems is present. Small changes in the system have had major impact. The founding of the IBA led to major changes in the system, not quite what the leaders of Jamaica may have intended. Systemic changes have a degree of irreversibility, and Australia and China emerge as leading producers and will continue to do so, mostly because this system requires massive capital investment. Aluminum firms in the private sector have survived, adapting to new realities. But they have less control over the system. Goldin and Mariathasan [36] considered the inherent systemic risk in globalization.

In the primary aluminum industry, we see adaptive behavior in two phases. First, the IBA broke the central hierarchical control of oligopolies, but were in turn overshadowed by Australia. This can be viewed as a market entity replacing a highly vertically integrated industry. Dynamics of the system were further provided by the breakup of communism. Russian production was highly innovative, researching alternative means of obtaining aluminum oxide through alunite and other materials. After the fall of the USSR, this source disappeared because it didn't prove to be economic under the new circumstances of profit orientation. Further goal-seeking is demonstrated by China, which counters the move to a free market with a different form of centralized control. All producers seek self-preservation, but economics can be seen to lead to shifts in trade patterns.

There has been unanticipated emergence demonstrated by Australian bauxite, taking over from the Caribbean in great part. The primary aluminum system has exhibited a possibly autopoeitic life of its own in transforming from a hierarchical system controlled by oligopolistic firms to a market system that has seen great growth in not only Australia but in China. In addition to the developments related to firm/producer country developments, the collapse of communism has played a role. Yugoslavia was becoming a major player in the industry, and while its remnants continue to produce, it is understandable that production there has declined. The Soviet Union's successor states also continue to play a role, with Russia relying on the aluminum industry as a means of production to gain economic ground.

The biggest message of observing the world primary aluminum industry is the emergence of supply chains of independent actors working together instead of a centralized hierarchy. This is not universal, as China is more of a controlled centralized decision making entity. Yet it participates in many international supply chains, making the aluminum industry an interesting example of a complex adapting system.

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Appendix

Statistics based on Mineral Yearbook published annually by the US Coast and Geodetic Survey, using reports on bauxite and alumina as well as for aluminum.

Table A1
World Bauxite Production

Country	**1970**	**1990**	**2000**	**2014**	*Change*	**Reserves**
Jamaica	11820	10900	11127	9800	*–2020*	2000000
Australia	9110	41400	53802	81000	*+71890*	6500000
Suriname	5927	3280	3610		*–5927*	580000
Guyana	4347	1420	2471	1800	*–2547*	850000
Yugoslavia	2600	2950			*–2600*	
Guinea	2451	15800	15700	19300	*+16849*	7400000
Indonesia	1210	1210	1151	500	*–710*	1000000
Dominican R	1050	85			*–1050*	
Haiti	622				*–622*	
Sierra Leone	433	1430			*–433*	
Ghana	337	381	504		*–337*	
IBA Total	**39907**	**78856**	**88365**	**112400**	*+72493*	**18330000**
USSR	4200	9250			*–4200*	
Russia			4200	5300	*+5300*	200000
India	1338	4850	7562	19000	*+17662*	540000
Brazil	492	9680	13866	32500	*+32008*	2600000
China	490	2400	9000	47000	*+46510*	830000
BRICS Total	**6520**	**26180**	**34628**	**103800**	*+97280*	**4170000**
France	2945	490			*–2945*	
Greece	2256	2500	1991	2100	*–156*	600000
USA	2082				*–2082*	
Italy	221	5			*–221*	
Turkey	50	773	459		*–50*	
Spain	5	1			*–5*	
Europe/US	**7559**	**3769**	**2450**	**2100**	*–5459*	**600000**
Other	2887	4195	9557	15700	*+12813*	
WORLD	**56873**	**113000**	**135000**	**234000**	*+177127*	**28000000**

Table A2
World Alumina Production

Country	**1970**	**1980**	**1990**	**2000**	**2010**	**2012**	*Change*
Australia	2372	7246	11200	15680	19956	20914	*+18542*
Jamaica	1892	2456	2870	3600	1591	1758	*–134*
Suriname	1118	1316	1530	1800	1486	1420	*+302*
Guinea	672	708	631	541	597	150	*–522*
Yugoslavia	138	1058	1090				*–138*
IBA	**6192**	**12784**	**17321**	**21621**	**23630**	**24242**	*+18050*
Russia*	2000	2700	5900	2850	2930	2719	*+719*
India	360	500	1600	2280	3640	4347	*+3987*
China	280	750	1460	4330	29000	37700	*+37420*
Brazil	131	493	1660	3743	9433	10000	*+9869*
BRIC	**2771**	**4443**	**10620**	**13203**	**45003**	**54766**	*+51995*
USA	7148	6810	5230	4790	3468	4387	*–2761*
France	1246	1173	50	200	481	540	*–706*
Japan	1416	1936	481	369	300	250	*–1166*
Canada	1218	1202	1090	1023	1301	1397	*+179*
Germany	895	1651	972	652	1485	1364	*+469*
United King	118	102	115	80			*–118*
Europe/NA	**12041**	**12874**	**7938**	**7114**	**7035**	**7938**	*–4103*
Other	1885	3325	6721	9762	9832	9454	*+7569*
WORLD	**22889**	**33426**	**42600**	**51700**	**85500**	**96400**	*+73511*

Table A3
World Primary Aluminum Production

Country	**1972**	**1980**	**2000**	**2010**	**2014**	*Change*
China	220	312	2640	23000	32500	*+32280*
USSR/Russia	1578	2298	3200	4440	4180	*+2602*
Canada	1035	1238	2370	3020	2990	*+1955*
India	227	380		1950	2890	*+2663*
Dubai		149		1800	2400	*+2400*
USA	4744	5503	4270	3200	2330	*–2414*
Brazil	113	306	1260	1700	1700	*+1587*
Australia	253	380	1770	2050	1630	*+1377*
Norway	762	773	1020	1230	1230	*+468*
Bahrain	132	132		880	970	*+838*
Iceland	83	95		790	840	*+757*
Saudi Arabia					740	*+740*
South Africa	57	94	676	900	715	*+658*
Germany	657	905		620	620	*–37*
Qatar				585	610	*+610*
Mozambique				570	570	*+570*
Argentina		154			455	*+455*
others	4405	5996	8594	6765	6330	*+1925*
World	14266	18715	25800	53500	63700	*+49434*