When materials become critical : lessons from the 2010 rare earth crisis
Sprecher, B.

Author: Sprecher, Benjamin

Title: When materials become critical : lessons from the 2010 rare earth crisis

Issue Date: 2016-06-28

4 Theoretical background of the resilience framework

In this chapter an overview of theoretical concepts is presented that will be used in the next two chapters to describe and assess the resilience of the NdFeB supply system. It is anticipated that this case study will have wider relevance for critical material supply chains. The first section discusses the social sciences concepts used to understand how the individual actors in the NdFeB supply chain behave and interact with each other. The following section introduces the concept of complex adaptive systems as the general theoretical background for understanding what kind of system the NdFeB supply chain is, from which resilience follows as the theoretical framework to analyze the problems surrounding the NdFeB supply chain.

4.1 Social Sciences theoretical background

This section follows Boons and is mostly based on his book *Creating ecological value*,[1] combined with some elements presented in his paper *Dynamics of industrial symbiosis.*[2] The work of Boons deals with how individual firms shape their ecological strategies to deal with emerging environmental problems, and how these firms interact to shape the dynamics at the system level. There were two main reasons for using the work of Boons. Firstly, Boons uses the company as the basic unit of analysis and explicitly places this company in a larger context, and specifically investigating the interaction between companies in a network. Secondly, Boons includes intangibles such as knowledge and legitimacy, which is an important aspect to the success of circular economy projects, yet not often addressed in industrial ecology literature.

In accordance with *Creating Ecological Value,* the socio-technical system can be looked at from three levels of analysis:

- The *production-consumption system*. Society has certain needs, which the production-consumption system meets by converting materials into services (e.g. the need for energy can be met by the producers of wind turbines or PV panels).
- The NdFeB *supply chain*. The collection of actors that cooperate to provide the NdFeB required by the production system to provide its services (e.g. direct-drive wind turbines).
- The *individual company.* The basic unit of analysis in this framework.

4.1.1 The production consumption system

When viewed from the production-consumption system level, change is often framed in evolutionary terms, both by Boons and in industrial ecology literature.[3] After Boons,[1] the main evolutionary mechanisms through which companies adapt to changing conditions are:

Coercion: an organization is forced to adopt a certain concept or routine by another organization that holds power over it, such as the government issuing a rule. Coercion is very evidently in play when looking at the 2010 Chinese export blockade and all its repercussions, for example multinationals moving the factories of NdFeB containing products to China because the price of NdFeB is significantly lower in China because of export restrictions and taxation (see also the discussion of research question 4, conclusion section in Chapter 7).

Imitation: organizations may adopt routines and concepts they see in similar organizations.

Private interest governance: a group of organizations may choose to collectively adopt a concept or routine voluntarily, because of the threat of legislation if they remain inactive. For example, the current standardized format for describing the different qualities of scrap metal are too coarse for high-level recycling. The International Solid Waste Association (ISWA) is currently in the process of identifying new material quality standards more befitting a circular economy.

Demonstration projects: actors may initiate experiments with new concepts and routines, and actively spread the results of these under a label like 'best practice' to accelerate its diffusion. For example, VGG actively pursued C2C projects with interested other companies. Even though many were not instantly profitable, they were pursued in the hope of demonstrating the viability of the concept.

Training and professionalization: individuals may learn about new concepts and routines through education, and subsequently start to apply these in their work environment.

Choi suggest that allied companies in a complex supply network should try to improve their cooperation through common work norms, procedures and shared language.[4] This notion of creating a shared language can go a long way in alleviating coordination problems and can be done through training programs and workshops. For example, after VGG came into contact with C2C it sent hundreds of its personnel, including the upper management, to Hamburg for C2C training by EPEA. The effect of this was an increased willingness in the company to work with C2C.

Altering boundary conditions: actions to stimulate actors within resource networks to self-organize. For example, the main driver for this research project is perceived future resource scarcity and sustainability. In that sense one might argue that the looming resource and energy crisis form an altering boundary condition that stimulate actors to self-organize.

In Chapter 5 we will identify mechanisms that were triggered in the NdFeB supply chain in response to the 2010 REE supply disruption. The above set of principles can usefully be seen as

the evolutionary mechanisms that underlie the ability of the NdFeB supply chain to react to such supply disturbances.

4.1.2 Supply chains and resource networks

The NdFeB supply chain (or any supply chain for that matter) requires a large number of disparate inputs in order to operate. This makes a complete supply chain quite complicated to analyze from a network point of view. Therefore, Boons proposes to use resource networks as the unit of analysis. These networks are a subset of the overall supply chain network that only deal with a single type of resource. These are not only physical resources, but also with intangibles such as knowledge and social resources such as legitimacy. Boons distinguishes between four types of resource networks: economic/material exchange, knowledge, rules, and collective perceptions & societal demands.

Boons hypothesizes that the creation of closed-loop material systems is aided by a high level of institutional capacity, which is defined as "an array of practices in which stakeholders, selected to represent different interests, come together for face-to-face, long-term dialogue to address a policy issue of common concern".[2]

Using the concept of resource networks (that deal with different types of resource, both physical flows and intangibles such as information) allows us to separate the discussion on physical flows and intangibles. The work in this dissertation is mostly based on the physical part of the supply chain. The work on intangibles is reflected in the MSc thesis *Information exchange and collaboration in recycling supply chains: Lessons from the paper and plastic recycling industry* (Valstar 2013).

4.1.3 Companies

As discussed in the introduction of this chapter, the research results in this dissertation are mostly on the level of the overall NdFeB supply chain. In order to give a complete theoretical framework, this paragraph will briefly discuss the types of environmental strategies that companies commonly follow with regards to adapting their behavior to a changing environmental context. Boons distinguishes companies according to their overall strategy in reacting to environmental challenges. These three basic 'strategic perspectives' are:

- Stable; which more or less equates to conservative; companies want to keep the status quo. Their environmental strategy can for instance be obtaining illegally smuggled material if regular supply becomes unavailable. Examples from outside the field of material criticality include resisting environmental regulations or only applying end-of-pipe pollution reduction measures.

- Dynamic; these companies tend to go with the flow. They could for instance try to weather material crises by relying on stockpiles or substituting critical materials.

- Transformative; companies that really try to transform the system. For example, invest in vertical integration to ensure a steady supply of raw materials, or focus on product-service systems so that the materials used by these companies remain in their ownership.

In order to following a general strategy, a company needs a collectively shared perception of the ecological impacts created by the company, and the possibilities for dealing with this impact. For example, the 2008 annual report of VGG states that:

> 'Cradle-to-Cradle is leading for our approach to waste management. This philosophy is based on possibilities instead of "guilt management". It also is our drive for giving sustainability a place in our daily routine. Our knowledge of waste is valuable for our partners. With them we can play a role in the design phase of their products, so that a profitable solution is possible.'

At VGG, resource scarcity plays a much larger role than global warming or biodiversity. This is due to the fact that resource scarcity very directly affects the day-to-day business of the company, in the form of rising prices they receive for recycled materials. In this sense, VGG's embrace of resource scarcity as a key driver for its sustainability commitment is logical as it presents an opportunity rather than a threat. Other aspects such as the impacts from emissions are dealt with in a more conservative fashion, with factories adding end-of-pipe technologies to reach emissions levels required by legislation. In this sense VGG is a transformative company on its primary business domain (resources), while having a stable strategy to deal with environmental concerns outside its immediate area of interest.

Boons uses the concept of routines to describe how companies actually implement their environmental strategies. Routines are procedures that have proved their usefulness. They represent knowledge that is somehow embedded in the organization's structure, culture or processes. These routines are used by a company to attain the goals set in its general strategic orientation. Boons distinguishes three dimensions of organizational routines:

- Operative routines; the knowledge and organizational abilities for getting the actual work done.
- Coordinative routines; the knowledge and organizational abilities for coordinating activities with other companies, for instance partnerships with suppliers or competitors.
- Formative routines; the knowledge and organizational abilities to shape the context in which operative routines are taking place. These routines are intended to influence the wider system surrounding the company so that the activities of the company are considered legitimate. For example, marketing to influence public opinion or lobbying to influence legislators.

An interesting point related to coordinative routines is that the recycling industry works with certain specifications, for instance the EU scrap specifications.[5] These are very general. For VGG to become a provider of raw materials, the recycled material will need to comply with much tighter specifications, comparable to that provided by primary production. During discussions at VGG it was often mentioned that better sorting and processing to achieve these high quality specs is not profitable since no-one is willing to pay extra for pure materials. This is probably a chicken-egg problem, but nevertheless it is clear that for a circular economy the quality of recycled material must improve drastically.

4.2 Complex Adaptive Systems theoretical background

In this section the basic theoretical concepts behind complex adaptive systems (CAS) will be reviewed, providing a further theoretical basis for the following two chapters. We start with a short description of the main characteristics of complex systems, and then conclude that resilience is a suitable concept through which to apply the insights gained from complex systems theory to the problems faced by complex supply chains such as that of NdFeB.

According to Dijkema & Basson, complex systems 'are characterized by diversity, multiple interactions both within and between layers, feedback loops, and emergence'.[3] Waldrop more formally defines complex adaptive systems as:

> 'A dynamic network of many agents (which may represent cells, species, individuals, firms, nations) acting in parallel, constantly acting and reacting to what the other agents are doing. The control of a CAS tends to be highly dispersed and decentralized. If there is to be any coherent behavior in the system, it has to arise from competition and cooperation among the agents themselves. The overall behavior of the system is the result of a huge number of decisions made every moment by many individual agents.'[6]

Competition and cooperation among agents is also indirectly referred to in the social sciences section, which describes change on the system level in evolutionary terms (section 4.1.1). In this sense the social sciences section provides an interpretation of the complex NdFeB supply chain system.

Examples of complex adaptive systems range from schools of fish to ecosystems to the human brain. Recently complexity theory has increasingly been used to understand the functioning of our society. For instance, an essay in Foreign Affairs argued that the collapse of empires throughout history should be seen as a function of the fact that empires are complex adaptive systems, which fail when they can't resolve inevitable issues with resource constraints.[7] A commentary in *Nature* lamented that our current economic system is badly mismanaged because monetary policies are based on statistical models that are inherently incapable of adequately describing the more extreme, non-linear, behavior of the global economy, caused by the fact that the economic system exhibits behavioral traits of complex systems.[8] *Science* reported how complex systems-based modelling was able to predict the eruption of ethnic violence in India and former Yugoslavia based on a characteristic group size of people that prefer similar neighbors.[9] Nissim Taleb wrote a popular science book on the consequences for our personal lives of erroneously interpreting a complex system as a linear system.[10] And finally, complexity theory is also fundamental to industrial ecology where sustainability is seen as an emergent property of our society.[3,11]

The journal of Industrial Ecology has dedicated two special issues to the topic (April 2009, Volume

13, Issue 2, and April 2015, Volume 19, Issue 2). This growing interest in complexity from the industrial ecology community is because complexity theory and related methods '… can help us determine how these systems shape both the relation and the mutual impact between us humans and the planet. It provides information to underpin policy and strategy for sustainable development',[12] and adds a very useful dynamic aspect to the traditional toolbox of LCA and MFA.[13]

The remainder of this section contains a discussion of relevant attributes and aspects of complex systems. Concepts such as emergence and feedback loops are core concepts in the resilience framework presented in Chapter 5, while it will become apparent that path dependence plays an important role in substitution options, because having more substitution options implies that your product development is not as dependent on the previous path it has taken.

4.2.1 Emergence

In industrial ecology literature (un)sustainability has been defined as emergent behavior of our social system.[13] A definition of emergence is 'the arising of novel and coherent structures, patterns and properties during the process of self-organization in complex systems',[14] resulting from many agents interacting with each other according to relatively simplistic rules (also known as fundamental rules). A classic example of emergent behavior is that of schools of fish:

> '[The emergent behavior is] based on fundamental behavioral rules such as attraction, parallel-orientation, and repulsion. Multiple individuals following the same rules interact with each other and thus realize school movements. When the school advances, unstable movements by the front individuals cause a change in the moving direction of the individuals that follow that individual. The transmission of the change in moving direction of the front individuals to rear individuals depends on how the individuals react to the motion of their neighbors. When the individuals react mainly to the motion of their front neighbors, the change in direction of the front individuals is transmitted quickly to the rear individuals, resulting in sharp turns by the school. In contrast, when the individuals react mainly to the motion of their side neighbors, the change in direction of the front individuals is slowly, if at all, transmitted to the rear individuals, resulting in only gradual turns by the school.'[15]

A unique feature of human society as a complex adaptive system in comparison to schools of fish is the fact that humans are not only adaptive but also reflective. That is, humans reflect upon society and this thinking informs human action, through which we manipulate the fundamental rules of society in order to obtain the desired behavior (but also unintended consequences). Rotmans & Loorbach distinguish 'three different types of emergence: discovery, mechanistic emergence, and reflective emergence. In systems exhibiting the latter type of emergence, the observers are among the objects of the system and have some reflective capacity, which enables them to observe the emergence they produce.'[16]

When applying this distinction to the NdFeB supply chain, one might theorize that the emergent resilience responses to the 2010 REE crisis are a form of mechanistic emergence; the actors in the supply chain did not reflect on the crisis but reacted more or less blindly, for example substituting a materials after it has become prohibitively expensive. On the other hand, when actors now decide to redesign their products to facilitate future substitution, this is an act under the umbrella of reflective emergence. With respect to the conclusions drawn from this research project, the entire dissertation can be framed as an exercise in reflective emergence.

4.2.2 Feedback loops

An important feature of complex systems is that they react non-linearly to input. This behavior is caused by feedback loops and can be explained by looking at the fundamental rules of a system. If you change something that goes against the fundamental rules, its effect will be damped because the fundamental rules are applied a huge number of times by all of the agents in the system. This is the negative feedback loop. On the other hand, if something happens that is amplified by the fundamental rules, or even a change in the fundamental rules themselves, it will propagate very fast throughout the entire system, also known as a positive feedback loop. This extreme change (relative to the input) will then interact with other parts of the system that could again involve positive feedback loops, leading to completely unpredictable but potentially very extreme changes.

According to literature, changing the fundamental rules in a complex system seems a matter of applying the goldilocks principle: not too much but also not too little. Rotmans & Loorbach write that "immediate radical change would lead to maximal resistance from the deep structure, which cannot adjust to a too fast, radical change. Abrupt forcing of the system would disrupt the system and would create a backlash in the system because of its resilience. Incremental change allows the system to adjust to the new circumstances and to build up new structures that align to the new configuration."[16] On the other hand Choi notes that the tendency of a complex system to maintain its stable and prevalent configuration works against incremental changes that go against the accepted practices. Therefore a meaningful change has more chance of lasting.[4]

In summary, the literature suggests that the most effective way of changing the emergent behavior exhibited by complex adaptive systems is by creating novel positive feedback loops.

4.2.3 Complexity and complicatedness

Complexity is not the same as complicatedness. Although they can be difficult to differentiate, distinguishing between the two is important because, according to Allan & Tainter, increasing the complexity of a system could solve problems while increasing complicatedness actually worsens these problems.[17] An example: suppose we have an ecosystem with only herbivores, which leads to overgrazing. Adding another species increases the number of elements in the system. The system becomes either more complex or more complicated. Conversely, adding a herbivore would make the system more complicated while not solving the problem of overgrazing. Adding a carnivore on the other hand would add a completely new layer of organization to the ecosystem, thus increasing complexity.

An example more closely related to the subject of resource constraints: in ancient Roman times copper could be mined in the hills around Rome at 20% ore concentration. Today we still mine copper ore, but at much lower concentrations, and at much remoter locations. Even though theoretically enough resources remain, the law of diminishing returns dictates that the costs of extracting these resources are increasing. As found in Chapter 6, one of the most forceful system responses to the 2010 REE crisis was to open new mines. However, this method of dealing with problematic resource extraction by increasing resource extraction amounts to replication of structure, and thus increasing complicatedness.

The most obvious way to increase complexity is by adding a different type of species to the REE ecosystem: recyclers. Although a single small recycler won't have much of an impact on the system level, once recycling incurs lower costs than mining, a positive feedback loop can be established with the potential to reorganize the supply chain.[17] The fact that this positive feedback loop was not established in the REE sector is discussed in Chapter 7.

4.2.4 Path dependence

The evolution of complex adaptive systems is inevitably path dependent and often irreversible, leading to lock-in. This is a problem because complex adaptive systems are fundamentally unpredictable (e.g. when fossil fuels started to be used climate change was not a big concern). Having expensive, fixed technological pathways that operate in unpredictable systems is undesirable.

Take for example our transport system: if one could re-design the world from the ground up, maybe cars could be replaced with a radically different and more efficient transport system. However, the huge investments in roads, technologies, vehicles, etc. mean the sunk costs and vested interest are simply too large to abandon the system.

4.2.5 Complex Adaptive Systems and resilience

Complex adaptive systems are unpredictable and difficult to manage. They are not only unpredictable, but even their unpredictability is unpredictable, meaning that one cannot even make an uncertainty estimate. The chances of these kind of extreme events are low, but as a system becomes more complex and interconnected the odds of an extreme event becomes ever greater. The 2010 REE crisis is a good example, which was initially caused by a completely unrelated diplomatic incident between Japan and China.

It is very difficult to plan for this kind of uncertainty.[1] Fortunately, complexity theory also suggests a coping strategy in the form of resilience, which has been argued to be in itself an emergent behavior of complex systems.[18]

Although a massive amount of scientific literature is available on resilience, the starting point of the resilience work presented in this dissertation was Wardekker et al.,[19] who formulated a number of resilience strategies:

1 Related to the concept of post-normal science.

- Homeostasis: multiple feedback loops counteract disturbances and stabilize the system.
- Omnivory: vulnerability is reduced by diversification of resources and means.
- High flux: a fast rate of movement of resources through the system ensures fast mobilization of these resources to cope with perturbations.
- Flatness: the hierarchical levels relative to the base should not be top-heavy. Overly hierarchical systems with no local formal competence to act are too inflexible and too slow to cope with surprise through rapidly implementing non-standard highly local responses.
- Buffering: essential capacities are over-dimensioned such that critical thresholds in capacities are less likely to be crossed.
- Redundancy: overlapping functions; if one fails, others can take over.

Interestingly, flatness is the opposite of increasing complexity, as discussed in the preceding section. According to Allan & Tainter increasing complexity of a system has the potential to solve problems, but also increases the risk of system collapse when not enough resources are available to support that level of complexity.[17] Therefore it makes sense that there is a point at which a system becomes overly complex, reducing the resilience of that system.

Meerow & Newell published a review of resilience and industrial ecology, showing that there is limited but growing interest in the topic.[20] Topics of research were eco-industrial parks, urban ecology, the built environment, recycling, and energy, water, food, economic, and agricultural systems. They also performed a network analysis, finding that the five most clusters research topics of resilience in IE were: (1) topically diverse; (2) risk and resilience in technical systems; (3) IE and resilience; (4) urban systems; and (5) agricultural systems. Meerow & Newell then conclude that 'given the emerging importance of the resilience concept and its relevance for sustainability issues, industrial ecology should expand research efforts in this area,' which is exactly what this dissertation aims to do.

A further review of literature specifically relevant to resilience in material supply chains can be found in Chapters 5 and 6.

4.3 References

1. Boons, F. *Creating Ecological Value*; Edward Elgar Publishing Limited, 2011.
2. Boons, F.; Spekkink, W.; Mouzakitis, Y. The dynamics of industrial symbiosis: A proposal for a conceptual framework based upon a comprehensive literature review. *Journal of Cleaner Production*. January 12, 2011, pp 1–38.

4

3. Dijkema, G.; Basson, L. Complexity and Industrial Ecology. *Journal of Industrial Ecology*. 2009, pp 157–164.
4. Choi, T.; Dooley, K.; Rungtusanatham, M. Supply networks and complex adaptive systems: control versus emergence. *Journal of Operations Management*. 2001, pp 351–366.
5. *European steel scrap specification*; 2005; pp 1–6.
6. Waldrop, M. M. *Complexity: The Emerging Science at the Edge of Order and Chaos*; Simon & Schuster: New York City, 1992.
7. Ferguson, N. Complexity and collapse. *Foreign Affairs*. 2010.
8. Farmer, J.; Foley, D. The economy needs agent-based modelling. *Nature*. 2009, pp 685–686.
9. Lim, M.; Metzler, R.; Bar-Yam, Y. Global Pattern Formation and Ethnic/Cultural Violence. *Science*. September 14, 2007, pp 1540–1544.
10. Taleb, N. *The black swan*, 2nd ed.; Penguin Books, 2011.
11. Hall, J. Environmental supply chain dynamics. *Journal of Cleaner Production*. Elsevier 2000, pp 455–471.
12. Dijkema, G.; Xu, M.; Derrible, S.; Lifset, R. J. Complexity in Industrial Ecology: Models, Analysis, and Actions. *Journal of Industrial Ecology*. March 26, 2015, pp 189–194.
13. Ehrenfeld, J. R. Understanding of Complexity Expands the Reach of Industrial Ecology. *Journal of Industrial Ecology*. April 1, 2009, pp 165–167.
14. Goldstein, J. Emergence as a Construct: History and Issues. *Emergence*. March 1999, pp 49–72.
15. Inada, Y. Steering mechanism of fish schools. *Complexity International*. 2001.
16. Rotmans, J.; Loorbach, D. Complexity and Transition Management. *Journal of Industrial Ecology*. April 1, 2009, pp 184–196.
17. Allen, T.; Tainter, J. Supply-side sustainability. *Systems Research and …*. 1999.
18. Gunderson, L. H.; Holling, C. S. *Panarchy: understanding transformations in systems of humans and nature*; Island Press, 2002.
19. Wardekker, J. A.; de Jong, A.; Knoop, J. M.; van der Sluijs, J. P. Operationalising a resilience approach to adapting an urban delta to uncertain climate changes. *Technological Forecasting and Social Change*. Elsevier Inc. July 1, 2010, pp 987–998.
20. Meerow, S.; Newell, J. P. Resilience and complexity: A bibliometric review and prospects for industrial ecology. *Journal of Industrial Ecology*. 2015.