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

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Title: When materials become critical : lessons from the 2010 rare earth crisis
Issue Date: 2016-06-28

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Framework for resilience in material supply chains, with a case study from the rare earth 2010 crisis

Reprinted with minor changes from: Sprecher, Benjamin, Ichiro Daigo, Shinsuke Murakami, Rene Kleijn, Matthijs Vos, and Gert Jan Kramer. "Framework for resilience in material supply chains, with a case study from the 2010 rare earth crisis." Environmental science & technology (2015).

5.1 Introduction

The 2010 REE crisis provoked a multitude of reactions across the entire NdFeB supply chain, ranging from dozens of junior mining companies claiming imminent rare earth production to end users reducing their reliance on neodymium magnets, or even substituting NdFeB completely.[1,2] The sum of these events resulted in prices falling significantly, if not actually reaching pre-2010 levels. Although the REE sector has many idiosyncrasies, when looked at from afar this type of boom-bust dynamics can often be observed when small raw material supply chains are integrated as supplier into a major industry.[3]

As the dust of the 2010 REE crisis was settling numerous reports and scientific publications investigated the rare earth sector, sometimes with diametrically opposed conclusions. For instance, Gholz writes that "the largely successful market response" offers the lesson that "policymakers should not succumb to pressure to act too quickly or too expansively in the face of raw material threats."[4] On the other hand, Tukker concludes that "Western governments ignored market failures" resulting in the fact that the Western world was "entirely outmaneuvered by an economy that was guided."[5]

More cautious analyses are made by Machacek and Fold, who focused on the efforts of Molycorp, Lynas and Great Western Minerals group to build a Western primary REE supply chain.[6] They give a good historical overview of events and conclude that the bottleneck for the establishment of alternative REE supply chains is at the chemical separation phase, because this technically challenging process is both expensive to build and operate. Golev et al. contribute a broader overview of several non-Chinese supply chains, discussing their opportunities and constraints in increasing primary production while also noting that there is industrial interest in recycling.[7]

Both Rademakers[8] and Sprecher[9] investigated the recycling opportunities for NdFeB, showing that recycling of magnets will most likely have limited effect on global supply. Seo and Morimoto compared recycling and substitution strategies from a Japanese perspective and concluded that substitution makes more sense because most of the Japanese REE demand is subsequently exported and not available for recycling to the Japanese industry.[10]

From this body of literature it is clear that the REE supply chain is a complex and intricately inter-linked system. However, previous work has for the most part only analyzed small parts of the system in relative isolation. We are not aware of any work that takes a broader systems perspective and uses a rigorous theoretical framework to analyse the resilience of the NdFeB system as a whole. This perspective allows the analysis of different aspects in a wider system context, whilst also investigating interactions between different parts of the supply chain. We feel this is especially relevant because it provides an interesting case study for more generally applicable insight into the ways supply chains of critical materials can respond to resource constraints and disruptions.

Based on an extensive literature review and interviews with actors ranging from large players such as Siemens and Hitachi Metals to individual entrepreneurs and government agencies, we developed a framework that aims to improve our understanding of how material supply chains respond to supply constraints and disruptions. We were guided by two research questions:

1) What type of mechanisms along the NdFeB supply chain provide resilience in response to supply constraints and disruptions?

2) What system perspective based policy recommendations can be made to improve the capacity of the NdFeB system to deal with future constraints and disruptions?

In our research, we used resilience theory as a framework to interpret the information we gathered from the interviews. Resilience can be defined as the capacity of a system to tolerate disruptions while retaining its structure and function.[11] Further below we develop a framework for the interrelated and complementary mechanisms that provide resilience in material supply chain, when these are confronted with resource constraints and disruptions.

In the remainder of this work we use ‘disruption’ to refer to quick, short-term supply disturbances and ‘constraint’ to refer to slower, long-term disturbances.

The resilience of systems has long been a subject of research, and is a recognized feature of many types of systems ranging from ecological to socio-technological.[12,13] We hope to advance resilience research by developing a novel and concrete framework that defines and clarifies resilience in material supply chains. Novel, because we are not aware of any research on the combination of resilience theory and resource constraints. Concrete, because we made extensive use of knowledge of the physical flows in the NdFeB supply chain. Our framework conceptualizes the dynamics of the NdFeB system in terms of resilience, and shows how and where distinct resilience concepts apply in the various stages of the NdFeB supply chain.

5.2 Method

Using a semi-structured interview format we first interviewed actors from across the NdFeB supply chain, as well as governmental and academic experts. 15 interviews were conducted in total. Seven interviewees were from Japan, seven from the EU and one from the US.

We then used the input from the interviews to build a qualitative representation of the NdFeB supply chain, using the system dynamics methodology introduced by J. Forrester.[14] As far as possible we used the same terminology as commonly used in material flow analysis.[15] This allowed us to map the socio-economical drivers on the physical flows in the supply chain, and visually represent at what places in the physical supply chain different mechanisms contribute to resilience.

NdFeB magnets often contain other rare earths in addition to neodymium, most notably praseodymium and dysprosium. For the sake of readability we will address these collectively by using the terms NdFeB and neodymium, except when relevant (in section 5.4.3).

Our results are based on information provided by the interviews, except where references to specific sources are given. The developed framework is our own work, that served to interpret the provided content in view of resilience theory. The full list of interviewees and the semi-structured interview questionnaire can be found in the supporting materials.

5.3 Resilience and the NdFeB supply chain

In section 5.3.1 we define supply chain resilience. Section 5.3.2 introduces rapidity, resistance and flexibility as the three system traits that together give rise to supply chain resilience. In section 5.4 we discuss the concrete mechanisms found in the rare earth supply chain that underpin rapidity, resistance and flexibility.

5.3.1 Definition and features of supply chain resilience

A more resilient system has properties that allow it to show limited consequences from disruptions and fast recovery times.[16] In the context of material supply chains we define resilience as *the capacity to supply enough of a given material to satisfy the demands of society, and to provide suitable alternatives if insufficient supply is available*. In practice this means that both the supply and demand of NdFeB will need to have a certain elasticity, which allows the system to absorb supply or demand disruptions without significant price fluctuations.

Although the literature mentions reduction of failure probabilities as playing an important role in enhancing resilience,[13,17-21] we stress that in the context of this framework we see resilience as the sum of several generic system dynamics, observable in material supply chains. These dynamics together enhance the overall response of the system to any kind of disruption, whether foreseen or unforeseen.

Our work could suggest that resilience is always good thing. However, whether this is true depends both on the boundaries of the system under investigation and the timescale under analysis.[11] It is worthwhile to note that the flip side of resilience is lock-in. Thus, short-term desirability for resilience can come in conflict with long-term desire for system change.

For example, the energy system could become more resilient, if more unconventional fossil sources were put into production. In the short term and from a local perspective the improved stability of energy infrastructure (energy security) is a positive. For instance, the increased production of light tight oil in the US has weakened the OPEC monopoly. However, if one enlarges the system boundaries to include the long-term perspective of society as a whole, the benefits of these huge investments in fossil energy and related infrastructures are less clear, because the lock-in created by these investments makes it more difficult to move away from using fossil fuels, thereby making our society less resilient against climate change. Here we note that the ecological literature offers a way out of lock-ins through adaptive capacity on a longer time scale (provided by a purging of nonfunctional system traits and innovation introducing new functional system traits), as it provides novelty to the functioning of supply chains. However, this mechanism was not mentioned by any of the experts interviewed.

5.3.2 Resistance, rapidity and flexibility: the cornerstones of resilience

In this section we introduce the concepts of resistance, rapidity and flexibility,[17,22] and use these to discuss how our case study relates to the larger socio-economical system it is embedded in.[23] But first we need to define our system boundaries clearly. We conceptualize our system as having three levels:

- Society; which has certain needs, such as transportation or energy.
- The production system; the system that meets the needs of society and is responsible for converting materials into services. For example, the need for sustainable energy can be met by the producers of wind turbines.
- The NdFeB supply chain; the system that provides the materials required by the production system to provide wind turbines to society.

We conceptualize the resilience of a system as depending on factors that either allow it to directly maintain function under disturbance, to rapidly recover from a disruption, or to switch between alternative systems that can provide the same service. More formally these are defined as:

- Resistance; the system maintains it function, i.e. it is able to tolerate various types of disturbances without experiencing unacceptable loss of function.
- Rapidity; the system is able to rapidly recover so that it meets its goals again within a short period following the disturbance.
- Flexibility; the system is capable of meeting supply needs under a disturbance by switching between different (alternative) subsystems.

The supply chain resilience framework is a clear example of industrial ecology, as all of the three resilience-contributing factors above have direct counterparts in ecology: 'resistance' is used to describe how ecological systems remain 'essentially unchanged' under disturbance; 'rapidity' is often defined in terms of 'return times to equilibrium' or in terms of the closely related resilience measure '1/return time', and 'flexibility' is used as such to refer to how consumers in ecological food webs switch between alternative resource types.[13,18-21]

Let us consider the previous example of energy: given the fact that society will need to switch to a sustainable source of energy to avert catastrophic climate change, it is desirable to have a resilient sustainable energy sector capable of meeting the rapidly increasing demands of society. Wind turbines are one of the main options for producing sustainable energy. Modern wind turbines can use either geared or direct drive technology. The latter utilises a large amount of NdFeB magnets, while the former requires specialty metal alloys for the gearboxes. Direct drive wind turbines are expected to increase in market share because they allow for higher efficiency and lower maintenance costs.[24-26]

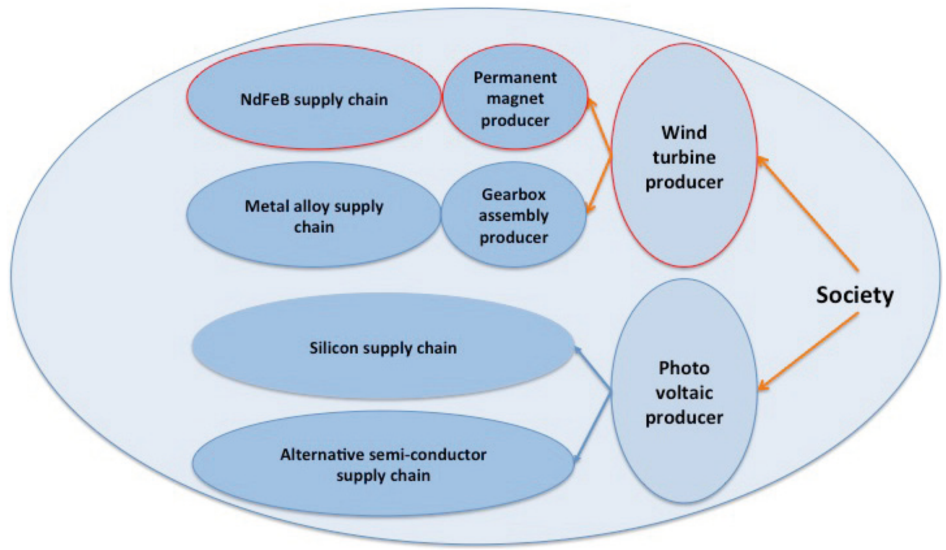

Figure 8 Resistance and rapidity depend on the strength of the system against disturbances. In this case the NdFeB supply chain, highlighted in red. Flexibility is the ability to switch between subsystems, and can occur on all levels of the overall system, highlighted in orange. Examples of alternative energy related supply chains are outlined in blue.

We would consider the wind turbine industry resilient if it is capable of providing sufficient wind turbines to fulfil the needs of society, even in the face of exponentially increasing demand and potential constraints and/or disruptions.

The resilience of the wind turbine system depends on the ability of the NdFeB system to provide a sufficient quantity of magnets to fulfil the demand for direct drive wind turbines (resistance)

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in the face of disruptions and/or constraints, and, if the NdFeB supply chain fails, on the speed with which the supply chain can recover (rapidity), or on the ability of the system to switch from producing direct drive to geared wind turbines (flexibility).

Figure 8 shows how resilience of the sustainable energy system depends on the resistance and rapidity of the actors within each level of the larger socio-economic system, as well as on flexibility between these levels. If demand for sustainable energy grows so fast that both the direct drive and the gearbox supply chains are not capable of keeping up with demand, society has the choice to use an alternative source of sustainable energy. For example photovoltaic energy, which will invariably have its own supply chain challenges.

A real-world example is Siemens, whose current generation of wind turbines is of the direct-drive type. It has invested in take-off agreements with the rare earth industry to ensure access to neodymium.[22] However, it also has geared wind turbine designs, ensuring that it can switch between alternative supply chains if this becomes necessary. Competing wind turbine producer Enercon has invested in direct-drive technology that functions without NdFeB magnets, using a synchronous generator and an electrical rotor instead.[25]

5.4 Mechanisms of resilience in the NdFeB supply chain

In the previous section we discussed at an abstract level how resistance, rapidity and flexibility contribute to resilience in material supply chains. In this section we use system dynamics to discuss which concrete resilience mechanisms we identified in the NdFeB supply chain.

As a reference point, Figure 9 shows the physical supply chain in the visual language of mass flow analysis. A more detailed description of the supply chain can be found in Sprecher et al. (2014).[27]

5.4.1 Diversity of supply

The Chinese export quotas were especially problematic because at that point in time China controlled 96% of the world REE production. Within China, two-thirds of rare earth oxides production originates from the Bayan Obo mine in Inner-Mongolia.[24] Clearly, such a narrow supply base is not robust. Therefore we introduce 'diversity of supply' as the first feature of a resilient material supply chain (note that this feature is closely linked to the concept of redundancy in resilience literature,[28] and to switching capacity. In this case not between alternative supply chains, but alternative providers of the same raw material).

In terms of system dynamics, having high diversity reduces the impact of a given disruption of the supply of REE ore to the rest of the supply chain. Figure 10 shows how we integrate diversity of supply into the NdFeB supply chain, which we conceptualize as the sum of primary production, post-consumer recycling and smuggling. Note that diversity of primary supply is only useful if the subsequent actors in the supply chain – in this case the REE refineries – have the technical and organizational capacity to switch timely between suppliers.

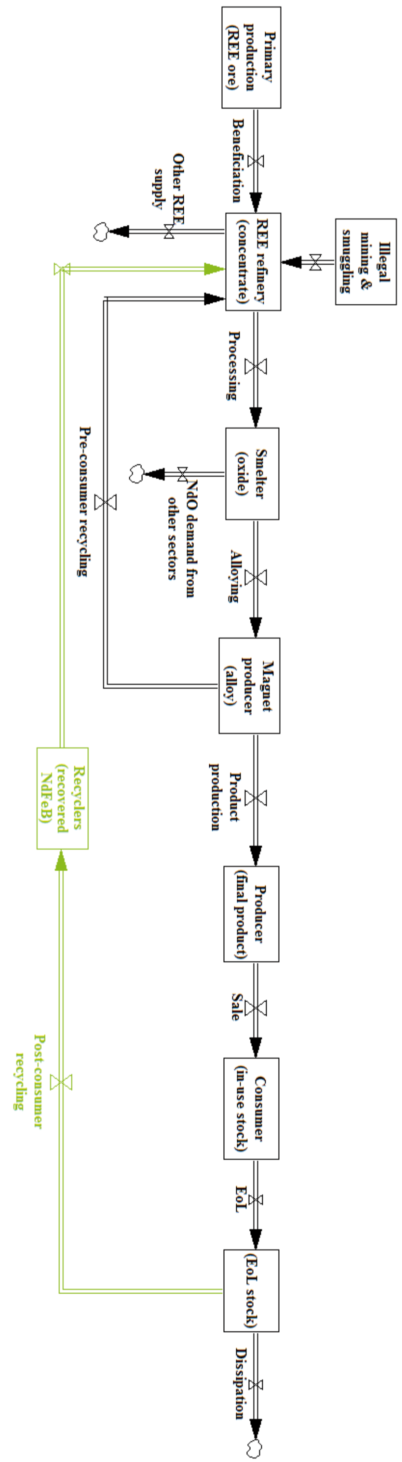

Figure 9 The NdFeB supply chain. Each box represents a stock of neodymium, while the form in which the neodymium is in that part of the supply chain is indicated between brackets. The arrows between the stocks represent physical flows of material, and are named according to the process used to transform the neodymium to its next form. Green indicates stocks and flows that do not currently happen on a relevant scale ('post-consumer recycling').

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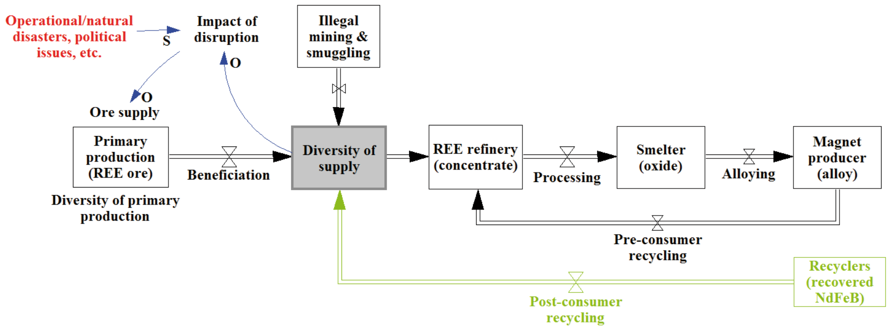

Figure 10 Diversity of supply: red indicates a system disruption or constraint. The blue arrows represent how the elements in the system influence each other: the arrowheads indicate the direction of the influence, the S or O next to the arrowhead indicate whether the connected parameters change in the Same or Opposite direction.

Primary production

The most obvious way to increase diversity is to have more mines, and to build mines in different countries. However, as Chinese attempts to buy REE mines in Australia and Greenland show, one should also pay attention to ownership issues, not just location.

Recycling

We distinguish between two types of recycling: pre- and post-consumer recycling.
In Figure 10 the green arrow represents the (at the moment of writing) mostly hypothetical option of recycling post-consumer waste magnets. Because of quality concerns, post-consumer recycling would in all probability lead back to the REE refinery stage, where the rare earths are extracted via acid leaching.[27]

Post-consumer recycling increases the diversity of supply because it can complement primary production. In contrast, pre-production recycling (the black arrow in Figure 10) of material lost during manufacture of the magnets (e.g. grinding losses) should be seen as a measure to increase production efficiency, which does not affect diversity of production.

Illegal mining & Smuggling

Besides the legal export of Chinese REEs, illegal sources can also provide a significant supply of raw material, estimated at one point to add 40% to official Chinese production.[29] This illegal material is either used in China or exported in the form of ore concentrates or oxides. The option of acquiring illegally exported material can reduce the impact of a supply disruption, but we note that smuggling and illegal mining go hand in hand with enormous social and environmental problems.[30] To simplify the figure we assumed all smuggling was in the form of concentrates. In India, illegal export of REE bearing monazite ore has also been reported in the press, albeit at a smaller scale.[31]

Other options

Finally, we would be remiss not to mention more exotic options such as deep-sea mining,[32] which, despite being challenging for technical, regulatory and environmental reasons, have significant disruptive potential because of the enormous amount of metals they could release into the market. Because interviewees indicated this is most likely still decades away we did not include it in our formal framework (interview Dr. Jiro Yamatomi).

5.4.2 Feedback loops through price mechanism

There are a number of feedback loops throughout the NdFeB supply chain. Here we will discuss the main feedback loop: the supply/demand price mechanism, shown in Figure 11.

Although in reality each actor in the supply chain has an associated supply and demand, we simplify this by representing supply as 'ore supply' at 'primary production'. This simplification still captures the essential system dynamics because, based on interviews, we infer that supply side constraints mostly exist at the beginning of the supply chain.

Increasing 'material demand' leads to a higher 'neodymium price' and vice-versa, while a high price will depress demand. Similarly, less availability of 'ore supply' causes an increase at 'Neodymium price'. This in turn will lead to 'investments in new primary production', which, after a significant time delay, increases the ore supply.

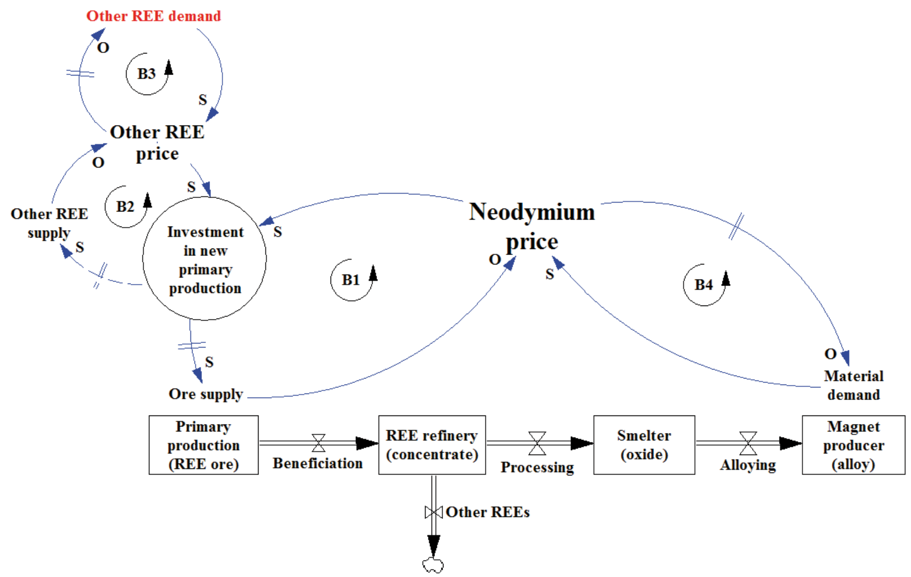

Figure 11 The supply/demand mechanism: feedback loops are represented with a circular arrow. The number is used to identify the feedback loop for further discussion. Feedback loops are identified by their number (B1), where the B indicates that this is a balancing feedback loop. The double dashed blue arrows indicate that there is a delay in the influence.

Because it is not possible to process a single REE without processing the majority of the associated REEs,[33] the primary production feedback-loop is complicated by the demand for other REEs. These are part of an identical feedback loop that also influences the decision to invest in new primary production. Although an important feature of many minor metals, the issue of co-mining is vital in rare earth economics. This means that increasing production of one high-demand REE will lead to overproduction of the associated REEs.

'Other REE demand' is coloured red, to indicate that it falls outside the system boundaries of this model. Note that in the full system dynamics picture (Figure 14), neodymium price also drives other factors such as investments in recycling. However, for clarity's sake we only describe the main feedback loop here. There are numerous other feedback loops discussed in the remainder of this work.

5.4.3 Material substitution and improved material properties

On the material demand side, a number of options are discussed in the material efficiency literature, such as increasing the lifetime of products, increase the use intensity of products (e.g. through products service systems) and the re-use of components.[34]
The NdFeB supply showed a more limited response with respect to reducing material demand. Interviewees identified two mechanisms that actors used to change their neodymium consumption.

Substitution
Substitution is the well-known switching mechanism whereby one material is substituted for a different material. There are many levels where substitution can occur, ranging from using a lower grade of the same material to outright substitution of the entire technological system dependent on that material (e.g. replace wind energy with PV). Based on our interviews we highlight the two most common types of substitution:

- Material substitution: the case where the requirement of using magnets remains in the final product design, but this requirement is fulfilled with a different material (e.g. replacing NdFeB magnets with samarium-cobalt magnets).

- Technological substitution: where a product is redesigned to operate without any magnets at all (e.g. replacing a direct drive with a geared wind turbine).

Changing material properties
Improvement of the properties of materials with the goal of reducing material usage represents a less drastic but more often realized measure (e.g. using grain boundary diffusion technology to allow magnets with lower levels of dysprosium to have equivalent high temperature operational specification).[10]

The distinction between substitution and material properties is relevant because they are different types of actions taken by different actors. As shown in Figure 12, substitution is done at the level of product design and relates to flexibility, while improving the material properties is done at the level of the magnet producers and relates to resistance.

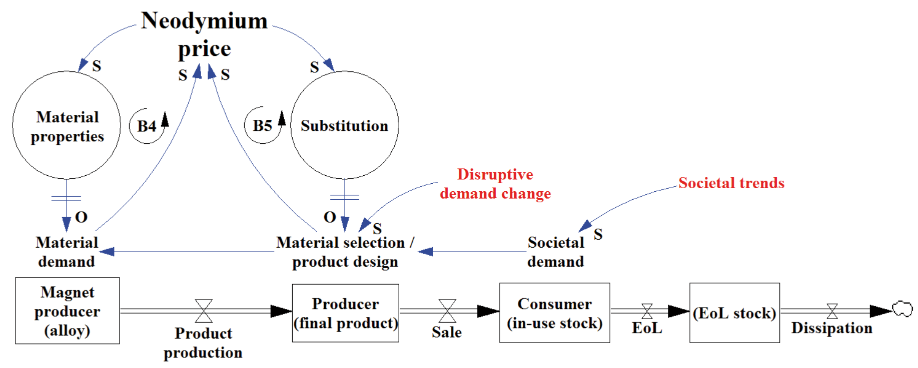

Figure 12 material properties and substitution: these have the same function (creating balancing feedback loop with price) but are implemented by different actors.

Figure 12 also shows how demand changes are incorporated into the model. Societal trends, such as increased demand for sustainable energy or smartphones, may change over time, leading to demand changes. At a lower system level, component changes may also lead to changes in demand (such as replacing LCD with OLED screens).

There are also two balancing feedback loops: substitution and improved material properties both reduce the demand for neodymium and/or dysprosium. This causes the price of NdFeB to go down, which in turn will lessen the need for further substitution or property improvement. Conversely, a low REE price can also lead to inefficient material use and cheaper production techniques that yield lesser material properties.

5.4.4 Stockpiling

Stockpiling can improve the resistance of the system, because a stockpile can absorb sudden price and/or supply fluctuations. However, stockpiling can also have a detrimental effect. During the 2010 REE crisis some Japanese companies forced their suppliers to increase their stockpile of raw materials to up to two years, at the very moment the prices were highest and the materials were hardest to obtain. This drove the price of neodymium and dysprosium up significantly (interview Hitachi Metals).

Because there are many different grades of NdFeB magnets, each with slightly differing alloying element ratios, it is difficult for magnet producers to keep significant stockpiles (interview Arnold Magnetics). Stockpiles are usually kept in the form of REE oxides, by the companies producing alloys.

Stockpiles also exist at country level. For example, the 2013 bi-annual US Strategic and Critical

Materials report recommended to stockpile $120 million in heavy rare earths,[35] and the Japanese independent administrative institution JOGMEC holds a 42 day stockpile for nine metals (Ni, Mn, Cr, Mo, W, Co, V, In, and Ga, but not REEs). Japanese companies are obliged by law to hold an 18 day stockpile.[36]

Finally, stockpiling can also be employed by speculators who aim to benefit from price volatility.

In our resilience framework we represent the stockpiling dynamic by adding a physical stockpile at the level of the REE smelter and a 'perceived short-term threat of supply disruption' parameter. Speculation played a (limited) role in driving up prices during the 2010 crisis[37] and is represented here at the same level as emergency stockpiling. Representing both the positive and negative effects of stockpiling, there are two competing feedback loops governing this mechanic:

- Reinforcing feedback loop: a supply disruption and/or a sharp increase in price increases the 'perceived short-term threat of supply disruption', which leads to emergency stockpiling by manufacturers and speculation. This drives up the material demand, which in turn increases price. A strong price increase in itself will fuel the perceived threat of supply disruption, leading to more emergency stockpiling.

- Balancing feedback loop: physical stockpiles act to reduce 'perceived short- term threat of supply disruption'. Increasing this stockpile through emergency stockpiling will reduce the perceived threat of supply disruption, causing a reduction in the need for emergency stockpiling.

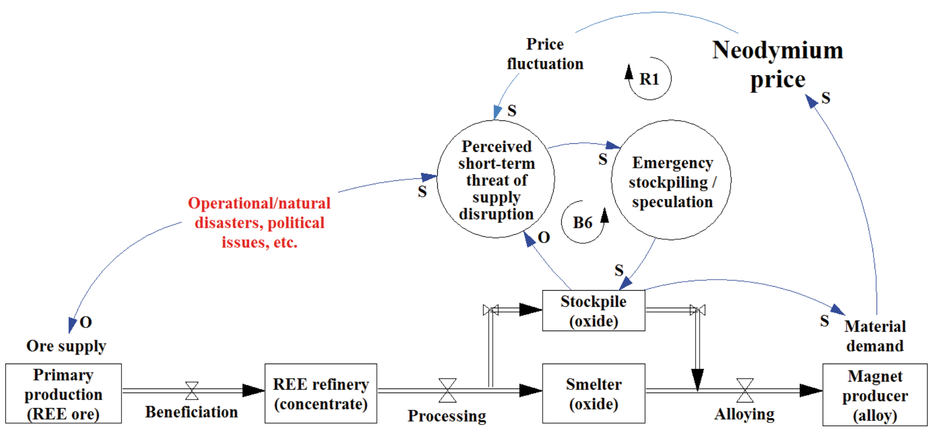

Figure 13 Stockpiling mechanic: in this figure we introduce the parameter 'perceived short-term threat of supply disruption'. This type of parameter is distinct from others in the model, because it shows how beliefs of actors in the system influence behaviour. It also features a reinforcing feedback loop (R1).

5.5 NdFeB supply chain system dynamics

In this section we look at the NdFeB supply chain from a complete systems perspective. First we discuss the different types of system constraints and disruptions, then the various system level interventions that could be implemented to improve resilience. Finally we combine the resilience mechanisms into a single system dynamics representation of the NdFeB system that shows how the various elements interact with each other.

5.5.1 Types of system constraints and disruptions

On an abstract level there are two types of system disturbances: those that affect supply and those that affect demand. These disturbances can range from fast to slow. As shown in Table 7, a sudden disruption of supply could be the result of natural disasters, such as the 2011 flooding in Thailand, or political issues such as the Chinese rare earth embargo of 2010. In the long-term, supply constraints could be caused by ore depletion or policies like export quotas and taxes.

A sudden increase in supply can come from governments releasing stockpiles. This happened for instance with tungsten in 1995: a sharp increase in price led to China, Kazakhstan and Russia releasing their inventories, which caused an oversupply situation.[3,9] A more long-term oversupply situation can currently be observed in the cerium market, a REE that is co-produced with neodymium. The increased demand for neodymium resulted in a cerium glut, severely depressing prices (interview Nissan).

Table 7 Types of system disturbances.

	Supply	Demand
Fast	Natural disaster, political issues	Disruptive demand change
Slow	Protective measures, ore depletion	Societal, technological trends

On the demand side relatively slow constraints come from societal and technological trends, such as increasing electrification and use of sustainable energy. Fast demand increases usually stem from either an exploding demand for a new type of product (e.g. smartphones), or from component changes in existing products (e.g. new generation of wind turbines switching from geared to NdFeB containing direct drive technology).

5.5.2 Options to improve supply chain resilience

Since the 2010 crisis several alternatives to Chinese primary REE production have come online, indicating that this is a mechanism that the NdFeB supply chain naturally resorts to in order to solve constraints. In this section we describe various other policy options to improve the resilience of the NdFeB supply chain.

Reduce red tape to improve system response times
Although laws and regulations often exist for a good reason (e.g. ensuring that the social and environmental consequences of new economic activities are well understood) they can also act as an impediment to system change. The long lead-time in obtaining permits is a frequently mentioned example of red tape leading to delay in building new primary production. On the recycling side an example of regulatory issues are the European waste laws. These can obstruct recycling because once a material is labelled as a waste it is difficult to use it as an end product again.

Companies and governments should work together to reduce the impact of regulations on the time needed to implement solutions, for instance through doing some of the work already in advance. For example, the German Rohstoffallianz provides its members with options to bundle interests from a value chain perspective and optimizing the supply planning horizon, for instance by drafting templates for framework take-off agreements (interview Rohstoffallianz).

Implement a mineral tax
One of the challenges with implementing a recycling scheme is that the prices of raw materials are often too low to warrant recycling. The production costs of primary production are lower than the collection and processing costs of recycling. Because of the supply/demand feedback loop, primary production will outcompete recycling. This is of course assuming sufficient reserves for increasing primary production, which for REEs certainly is the case. The same effect can be seen at the product design level with regard to efficient use of materials.

The principal reason for a mineral taxation scheme levied at primary production is to re-distribute the profit made from exploitation of non-renewable resources.[38] However, if a mineral tax were to be implemented on a significant (if not global) level, a secondary effect would that the increased costs of primary production can prevent the supply/demand feedback loop from steering the NdFeB system away from more sustainable material use, especially if some of the tax revenue would be used to support recycling.

Support R&D to expand use of excess REEs
A low consumption of other REEs can prevent investment in primary production. This is also known as market inelasticity, where an increase in demand does not translate automatically to an increase in supply. In order to solve this balance problem one could stimulate the demand for other REEs through focused R&D to find new applications.

For example, there is a trend to alloy magnesium with REEs to improve the creep resistance of magnesium alloys.[39] Creep resistant magnesium alloys are used for drive train applications in the automotive industry for purposes of weight-saving.[40]

Promote design for recycling
Products using NdFeB magnets are currently designed in such a way that separating the magnets is very difficult.[9] This is reflected in the fact that even when the price of neodymium increased dramatically, post-consumer recycling did not take off in any meaningful way. Even if recycling of some applications with large volumes of magnets would become feasible (e.g. wind turbines, electric vehicles), this still leaves the many applications of smaller magnets – weighing no more than a few grams – where recycling would be uneconomical under almost any circumstance. This also applies for the many other critical elements that are used in very low concentrations.
Implementing design for recycling principles and having waste regulations that are not mass based targets, but regulate which materials need to be recycled would in all probability improve this situation (interview Dr. Allan Walton).

Increase stockpiling
Stockpiles offer the possibility to completely negate the impact of any temporary supply disruption, albeit at significant capital costs. Especially for neodymium (and rare earths in general) there is a case to be made for stockpiling, because their costs are but a fraction of the overall value of the products they are contained in, meaning that a stockpile could acts as a relatively cheap insurance policy.[5]

However, as described in section 4.4, it does not make sense for end-users to stockpile neodymium, but rather the alloy producers, for whom the cost of neodymium is a very significant barrier to stockpiling. Although there is some ad-hoc stockpiling based on individual agreements between end-users and magnet producers (interview Arnold Magnetics), we suggest a common stockpile would be an efficient way to solve this problem. This stockpile can come with a pre-arranged protocol on how to divide its contents in case of an emergency. This would help to prevent actors from driving up the price by chasing the same stockpile, as happened in 2010.

5.5.3 Complete system dynamics of the NdFeB system.

In Figure 14 we combine the previously introduced system elements into a complete overview, which shows how and where the various resilience mechanisms interact with the physical stocks and flows of the NdFeB system. The green elements show the options to improve resilience, while the red elements show the various types of disturbances. Both disturbances and mechanisms to deal with disturbances are distributed across the entire system.

Having all of the various elements of resilience together in one figure illustrates that every part of the supply chain is somehow involved. Insofar that, especially in the aftermath of the 2010 REE crisis, the individual actors have relatively little information on the behaviour of other actors in the system, we consider resilience to be an emergent system property.

Compared to the individual resilience mechanisms there are also some minor additions. In order to recycling to 'Neodymium price' we add the 'investment in recycling infrastructure' parameter that mirrors the 'investment in new primary production' parameter.

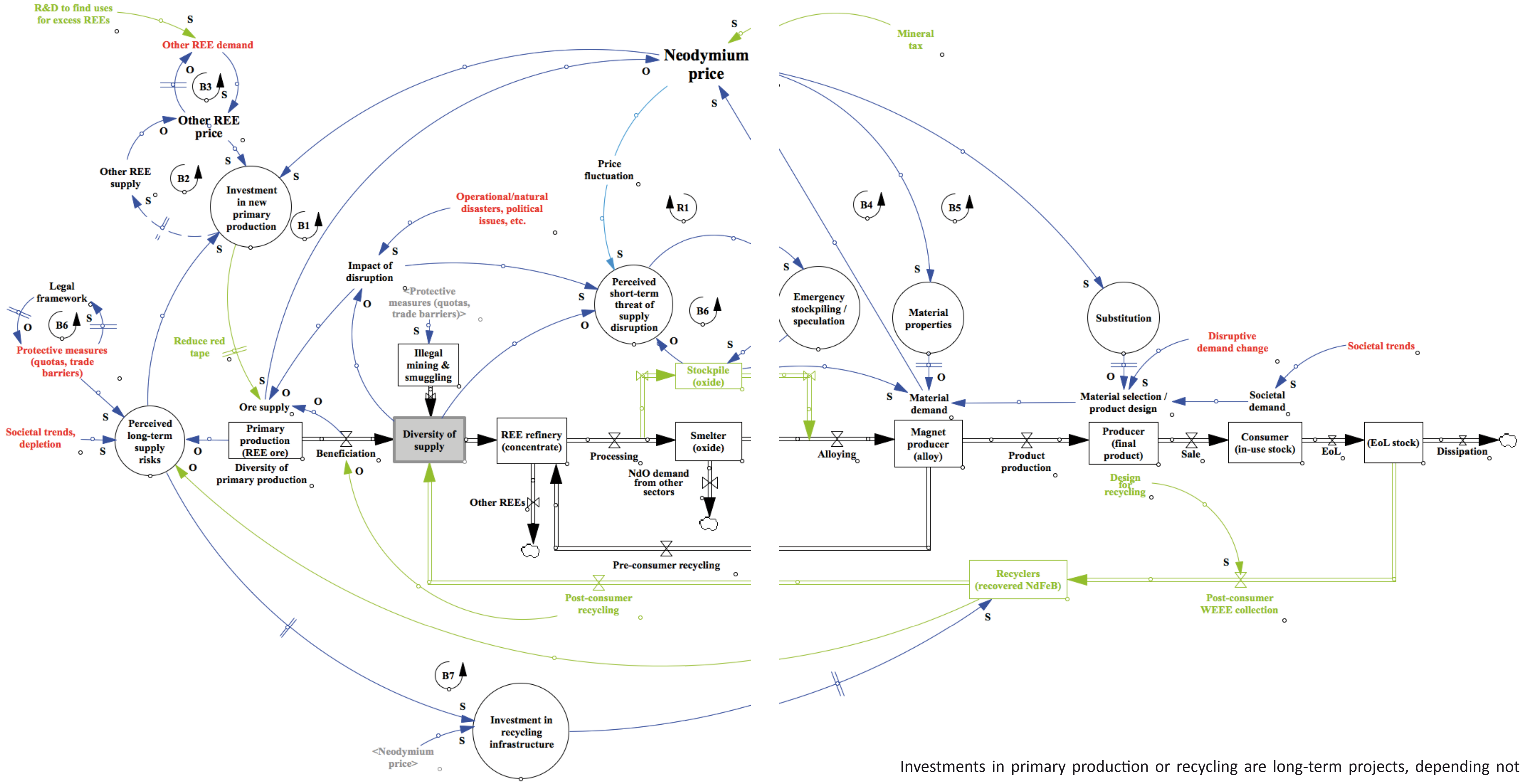

Figure 14 System dynamics of the NdFeB supply chain: this figure combines the resilience mechanisms from the previous section and adds some elements, as discussed in the text.

Investments in primary production or recycling are long-term projects, depending not only on the spot price of rare earths but also on the expected long-term demand. We model this by making long-term investments dependent on the 'perceived long-term supply risks' parameter, which accounts for slow trends such as depletion of existing mines, societal trends, technological developments and protective measures. One might expect that long-term supply risk is something that influences material selection choice at the product design stage, but according to our interviews this is not the case, and materials are selected solely on their economic and physical properties (interview Chatham House).

Finally, there is a minor feedback loop connected to 'perceived long-term supply risks' that covers the legal responses to protective measures by states, mainly in the form of WTO lawsuits.

5.6 Discussion

In this paper we provide a framework that defines and clarifies supply chain resilience. We demonstrated the use of this framework by analyzing the multiple responses of the neodymium magnet (NdFeB) supply chain to the 2010 Chinese export restrictions. As a consequence of these restrictions, the price of neodymium increased by a factor of 10, only to return to almost normal levels in the following months, despite the fact that the restrictions were not lifted (export quota have been lifted since 1 January 2015, but export licensing may substitute its restrictive effect).[41] These events indicate that the NdFeB supply chain was not very resistant to the disruption, but it recovered with remarkable rapidity.

Compared to previous literature discussing REE supply chains, our framework allows a more nuanced and complete analysis of how supply chains of critical materials respond to disturbances. Besides contributing to the understanding of NdFeB supply chain system dynamics, we also believe the framework to be of more generic relevance to those interested in material criticality and the resilience of material supply chains.

Through literature review and extensive interviews with actors across the NdFeB supply chain we have shown that resilience in the NdFeB supply chain is comprised of resistance (the ability to tolerate disturbances without unacceptable loss of function), rapidity (the ability to rapidly recover from a disruption), and flexibility (the ability to switch between alternative subsystems). We found that the following concrete mechanisms are primarily responsible for this resilience. On the supply side:

- Diversity of supply; more variety in sources of raw material potentially reduces the impact of a disruption or constraint on the remainder of the supply chain.

- Stockpiling; acts as a buffer that lessens the impact of temporary supply disruptions.

On the demand side:

- Improving the material properties; magnet producers have responded to supply constraints by improving the properties of NdFeB, greatly reducing the required amount of dysprosium for high temperature resistant magnets.

- Substitution; some producers substituted NdFeB magnets with other magnets, while others switched to a completely different technology that did not rely on permanent magnets.

The main stabilizing/destabilizing forces in the system are the feedback loops, of which the economic feedback loop (i.e. price mechanism) is the most important. Figure 14 gives an overview of how all the feedback loops and mechanisms are connected to the supply chain. Not all responses to the 2010 REE crisis contributed positively to system resilience. We note the two most explicitly negative responses. The first is panic buying by Japanese companies, who tried to increase their stockpile only after the Chinese export quotas came in full force. This contributed greatly to the

price increases. The second is illegal mining and smuggling of Chinese rare earths (estimated at 40% of the official production).[29] Although smuggling increases the diversity of supply and thus increases the resilience of the sector, illegal mining has devastating environmental and social effects.[30]

In the past several years the diversity of primary production has improved significantly, with several new primary production sources of REE becoming operational.[6] However, increasing the diversity is only one, potentially limited and exclusively supply-side focused lever that can be pulled in order to improve the capacity of the NdFeB supply chain to deal with future constraints and disruptions. We proposed five additional system interventions:

- Reduce red tape for faster system response times (i.e. legislation related to mining permits, recycling)
- Implement a mineral tax to promote more sustainable use of raw materials
- Support R&D to expanded use of REEs that are co-mined in excess
- Promote design for recycling
- Increase stockpiling to effective levels

Improving the rapidity of the system can be achieved by improving the robustness of production facilities against natural/operational disasters. This did not come up in any of the interviews, probably due to the fact that we did not succeed in interviewing actors related to the first stages of the supply chain, predominantly located in China.

In the introduction we discussed how Gholz argued that the NdFeB case study shows a "largely successful market response"[4] while Tukker wrote that it shows how "western governments ignored market failures".[5] Out of the above five system interventions – based on suggestions from actors in the NdFeB supply chain – only 'reduce red tape' is in favor of further improving the free market response, while the other four relate to intervening in the free market. From this we tend to agree with Tukker, that our case study indeed contains a certain amount of market failure.

Finally, we would be remiss not to discuss our framework in relation to the various critical materials methodologies that have recently been proposed. Most notably by Graedel et al., who present a very thorough analysis of how to measure and rank the criticality of metals, applied to REEs by Nassar et al.[42,43]

Although there are dissimilarities in timeframe and system boundaries, their dimensions 'supply risk' and 'vulnerability to supply disruptions' strongly overlap with our supply and demand side resilience mechanisms. However, there are significant conceptual differences. Our work is focused on the dynamic aspects of the supply chain; how it changes over time in response to disturbances, while the Graedel et al. framework essentially generates a static snap-shot of criticality. The latter acknowledges but does not take into account the fact that non-linearity plays an important role in complex systems; this framework incorporates non-linearity through the explicit use of feedback loops.

Furthermore, Graedel et al. consider environmental implications to be a dimension of criticality. It is an unfortunate fact that our interviewees indicated environmental considerations to be of little importance to their decision making process, and therefore is not explicitly included in our resilience framework.

Despite the differences there is a clear overlap between our framework and the frameworks proposed in the critical materials literature. The question is then: how do resilience and criticality relate to each other? We would go so far as to argue that one can define the criticality of a material in terms of how resilient its supply chain is.

Further development of supply chain resilience theory could greatly benefit from a body of mathematical work in theoretical ecology, that provides in-depth analysis of the causes and consequences of resistance, rapidity-like measures of recovery speed and flexibility, in complex ecosystems and food webs.[13,18-21]

It would be very interesting to see this framework applied to other supply chains than that of NdFeB magnets. We hope this paper will enable other researchers to look at leverage points, bottlenecks, and to develop policy options that take into account the full system surrounding the supply chains of critical materials.

Acknowledgements
We would like to thank Ibuki Komatsu for translating during the Japanese interviews, Van Gansewinkel Groep for their financial support and the anonymous reviewers for their detailed and constructive criticism.

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