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

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Discussion

In the preceding chapters we have considered a number of aspects of neodymium supply and recycling. This scientific enquiry was done in the context of the 2010 REE crisis. Neodymium is a generally recognized critical material with a relevant application in the form of NdFeB magnets, whose unique strength makes it a key component for sustainable energy technologies (direct-drive wind turbines and motors for electric vehicles) as well as in consumer goods (e.g. hard disk drives).[1,2] Additionally, material resource constraints are generally seen as important aspect of sustainability.[3] Therefore, the NdFeB supply chain makes for an interesting industrial ecology case study. Furthermore, the criticality of REE present an appropriate case study of what 'criticality' is, because for current demand there is more than enough REE bearing ore available across the globe. This implies that any near-future supply constraints are not the consequence of inherent problems with resource availability, but rather of a (mal)functioning of the supply chain. Finally, as a practical consideration, the NdFeB supply chain makes for a case that is quite 'small', i.e. one with a limited number of actors, and also compact in time, allowing us to track the process from initial disruption to re-equilibration of the system, even while the crisis is relatively recent.

This dissertation aimed to answers four main research questions:

1. What are the material flows of neodymium for NdFeB, and how much can be made available for recycling?
2. What are the environmental burdens of NdFeB production, and how does recycling alleviate this burden?
3. What type of mechanisms along the NdFeB supply chain provide resilience in response to supply constraints and disruptions?
4. Can we quantify the resilience mechanisms of the NdFeB supply chain, and identify which played the most significant role in the aftermath of the 2010 REE crisis?

First, in sections 7.1 through 7.4, we answer each research question separately. In section 7.5 we draw conclusions with respect to the overall NdFeB supply chain and in section 7.6 we discuss resilience from the perspective of each type of actor along the supply chain. In section we 7.7 discuss the merit of the resilience framework in comparison with other criticality-focused frameworks. We end with an outlook for future research (7.8).

7.1 The material flows of neodymium and their availability for recycling

The vast majority of neodymium is used for NdFeB magnets (88%, see Figure 2). We found that for most non-magnet applications neodymium is dispersed to such a degree that setting up a closed loop recycling system would be very difficult. However, even when restricting ourselves to NdFeB magnets, we find that its usage is spread among an enormous range of applications (see Table 1). Wind energy and e-mobility are often seen as significant potential recycling sources because they contain a large quantity of NdFeB magnets. However, literature shows that because of long lifetimes these magnets will probably not be available for recycling in large volumes in the next two decades.

Our results indicate that for the foreseeable future, the only available source of recyclable NdFeB is from computer hard disk drives (HDDs). We find that within the application of NdFeB magnets for HDDs the potential for loop closing is significant, up to 57% in 2017 (see Figure 5). However, the recovery potential from HDDs compared to the total NdFeB production capacity is relatively small (in the 1-3% range). Moreover, we found there to be severe barriers to NdFeB recycling, such as prohibitive costs, collection rates and uncertainty about future use of NdFeB for computer storage. These were discussed in more detail in Chapter 2.

Chapter 2 also addresses the question of what problems recycling would alleviate. Besides environmental concerns (see the following section), the discussion is often framed in terms of security of supply: OECD countries find it undesirable to be dependent on a single supplier such as China for virtually the entire supply of rare earths. Additionally, most of the basic processing facilities that are needed to produce neodymium magnets are to be found in either China or Japan. Insofar that measures to reduce resource dependency focus on recycling, these should not only emphasize the recovery of NdFeB from waste, but also the production capacity to reprocess the End-of-Life magnets into new material.

From the resource scarcity perspective we think that in the near future recycling neodymium will be able to contribute very little, due to the distributed nature of the applications. The fact that the whereabouts of a critical metal such as neodymium can only be traced for such a small fraction of the total use is undesirable because it makes it very difficult to formulate specific policy on for example what sectors to prioritize with respect to efforts to increase security of supply. We suggest that if neodymium is to be used sustainably, a concerted effort must be made to categorize the applications in which it is possible to create a closed-loop and only use Neodymium for these applications. The potential of recycling can be increased significantly if neodymium can traced from mine to material, product and finally to waste.

7.2 The environmental burdens of NdFeB production and the prospects of recycling

With respect to environmental impact of primary neodymium production, we found that if the primary production process of NdFeB is technically advanced (i.e. high process efficiencies, end-of-pipe emission controls), most of the impacts are related to energy use. Technically less advanced production processes also incur a large human toxicity penalty, which highlights the significant improvement potential for technical improvements in production processes. Our results indicate that a low-tech production process has double the GHG emissions of a high-tech process, while the Human Toxicity indicator increases by an order of magnitude (see Chapter 3 for detailed results).

We also found that in the baseline scenario of Chapter 3, 64% of the total neodymium input is lost along the production chain. Half of this loss occurs during the beneficiation process of REE containing ore. Peiró and Méndez report that recovery rate during beneficiation is expected to rise to 75% by 2016.[4] Such an improvement to the recovery rate in this process has the potential to significantly reduce supply side constraints of all REEs, not only neodymium, and should be prioritized over process improvements later in the production process.

With respect to recycling, we analysed two different processes: the traditional shredder–based process and a novel hydrogen–decrepitating process. Our results (see Figure 7) indicate that the choice of recycling method is of significant influence on the environmental impact, with hydrogen decrepitation scoring significantly better. However, the most important difference between the two recycling processes is not adequately reflected in the environmental indicators: recycling through shredding results in very low recovery rates (<10%) of NdFeB. Because the discussion on the use of rare earths is framed in terms of scarcity more than environmental damage, this is a serious issue not addressed through LCA.

We conclude that the value of recycling of neodymium is highly dependent on the method of recycling. Although from an environmental point of view recycling will always be an improvement over primary production, the large losses of material incurred while shredding the material puts serious doubts on the usefulness of this type of recycling as a solution for scarcity. Furthermore, our LCA also shows that technological progress can make a significant difference in the environmental impact of producing neodymium magnets from primary sources.

7.3 The mechanisms along the NdFeB supply chain providing resilience in response to supply constraints and disruptions

The research presented in Chapter 5 shows that resilience is a useful concept for investigating the dynamics of the NdFeB supply chain. It comprises aspects of resistance to disturbance, rapidity of response, and flexibility, *i.e.* the ability to switch between alternatives.

We found that the following concrete mechanisms are primarily responsible for this resilience. On the supply side *diversity of supply* allows for more variety in sources of raw material, potentially reducing 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 there is *improving material properties*, where magnet producers have responded to supply constraints by improving the properties of NdFeB, thus greatly reducing the required amount of dysprosium for high temperature resistant magnets, and *substitution*, where some producers substituted NdFeB magnets with other magnets, while others switched to a completely different technology that did not rely on permanent magnets. The three most common types of substitution are:

- Material substitution: the requirement of using magnets remains in the final product design, but this requirement is met with a different material (e.g. replacing NdFeB magnets with samarium-cobalt magnets).
- Technological substitution: a product is redesigned to operate without any magnets at all (e.g. replacing a direct drive with a geared wind turbine).
- Grade optimization: a high performance magnet is substituted by a low performance magnet with a lower REE content. This can be done almost instantly. Our impression is that Japanese manufacturers tried to obtain their material at any cost, while European manufacturers sometimes opted for temporarily using much lower grades of NdFeB, accepting that their products would not perform as advertised, although for obvious reasons this is a sensitive topic.

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 illustrates 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, in the sense that they aggravated rather than relieved the crisis. 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).[5] Although smuggling increases the diversity of supply and thereby the resilience of the sector, illegal mining has devastating environmental and social effects. [6]

7.4 A quantification of the resilience mechanisms of the NdFeB supply chain

The most salient of the findings presented in Chapter 6 is that the aggregate of substitution actions was the most significant system response. Substitution is highly dependent on the specific application. We found that some producers rapidly adapted to the increased prices by switching NdFeB for samarium-cobalt magnets, while others temporarily used lower-grade NdFeB magnets. A more thorough substitution type requiring product redesigns followed a year or two after the disruption. Overall, roughly 10% of the total market volume was substituted each year. Our research indicates that realistically up to 20-50% of NdFeB demand will be substituted, depending on future market conditions (i.e. price). Use of dysprosium as an alloying element was also reduced significantly, both by substituting dysprosium-rich NdFeB alloys for other alloys and by changing the production method of temperature-resistant NdFeB magnets.

Non-Chinese primary production also responded within a year. However, as seen in Figure 18, in terms of absolute production the ramp up was smaller than that of substitution (4% of total market volume per year, compared to 10% for substitution). Since truly new primary production capacity takes 4 to 13 years to come online, this relatively quick increase in primary production can be attributed to increased production of REEs in mines that normally only mine other metals, and for whom the increased REE price suddenly made co-production of REEs worthwhile.

Significant stockpiles were available at the beginning of the disruption. However, in the perception of NdFeB consumers, these stockpiles were not large enough to cover the time needed to implement measures such as substitution. This caused some actors to acquire more material at any cost, driving the price of REEs significantly higher than otherwise would have happened. Thus, rather than cushioning the supply disruption by releasing material from the stockpile, additional stockpiling actually worsened the disruption into a crisis. Interviewees indicated that the current level of stockpiling is 6 to 12 months for Japanese car companies, while European companies generally have a 2 to 5 week stockpile.

Finally, recycling is of note primarily because of its trivial impact on the market, due to the problems with collecting and processing NdFeB magnets from waste electrical and electronic equipment WEEE discussed in Chapter 2.

Taken together the resilience responses were of sufficient magnitude that the supply chain should have experienced less of a price shock than it actually did, especially considering the ease of substitution and the size of stockpiles relative to the magnitude of the disruption. In the following section we turn to analyzing the supply chain as a whole to understand why this was so.

7.5 Summary conclusions on overall NdFeB supply chain resilience

The supply chain as a whole was able to compensate for the 2010 disruption in less than two years. The combined effect of substitution and increasing non-Chinese production is shown in Figure 18. Two dynamics deserve to be highlighted: between 2010 and 2012 the resilience mechanisms were not able to compensate for the drop in production. During this same period some actors were increasing their stockpiles which led to a temporary increase in REE demand (section 6.3.5). Other actors compensated by drawing on their own stockpiles, using illegally sourced materials or even stopping their production altogether. After 2012, the resilience mechanisms overshot the gap in primary production. Substitution in this period can be interpreted as compensation for the demand growth that would have occurred post-2010 had there been no disruption.

It is reasonable to believe that the NdFeB supply chain system has become more resilient and diversified as a results of the crisis, which was caused as much by maladaptive system response (actors engaging in emergency stockpiling behavior) as by the initial disruption itself. While it is debatable to what extent a two-year response time can be seen as resilient, there is every indication that a new disruption will be dealt with more quickly, because a lot of the groundwork for the resilience mechanisms has already been done. However, for the system to be truly resilient, the current stockpiles should be large enough to provide resilience until the other mechanisms can take over. What this means exactly is highly dependent on the type of actor and product, but our interviewees indicated that one should generally aim for a 3-9 month stockpile. Given that our research indicates that the current level of stockpiling is 6 to 12 months for Japanese, and 2 to 5 weeks for European car companies, increased stockpiling might be advisable, especially for European companies (this might also be the case for other western companies, however, this was outside the scope of this research project).

The fact that substitution and replacement of primary production, and not recycling, were the main resilience mechanisms has important implications for the idea of a ‘circular economy’. Many reports on the circular economy will implicitly or explicitly adhere to reasoning along the lines of circularity being an easy fix for stagnating economies, resource constraints and climate change. For example, the Ellen McArthur Foundation writes that ‘resource productivity remains hugely underexploited as a source of wealth, competitiveness and renewal’,[7] and the International Solid Waste Association says that ‘price signals for raw materials are a key driver in any change to the circular economy’.[8]

The case study of Chapters 5 and 6 provided an example where a supply disruption and subsequent price peak did not nudge a system towards circularity in any appreciable degree. Although our study only discusses the effect of a single supply disruption, it is relevant to the overall discussion on material scarcity because of the significance and duration of the disruption. If a two-year disruption causes almost no movement towards more effective material use, then this implies that quite a long period of sustained material constraints will be necessary for a production-consumption system to naturally evolve towards a circular configuration.

If not effective in nudging a transition towards circularity, the REE crisis did have a different effect. Figure 16 shows that market concentration, as measured by the HHI indicator, is now higher for NdFeB production than for primary production, with production capacity increasingly being concentrated in China. This is not likely to be a problem from a supply chain disruption point of view, because sufficient technical capacity to produce NdFeB outside China exists. It does however show that the Chinese goal of leveraging its market dominance in REE production to force production further in the value chain to China is successful.

One last issue is the status of the NdFeB supply chain as a complex adaptive system. One of the defining elements of a complex system is that the agents inside the system act more or less blindly, which gives rise to unplanned emergent behavior. Based on the reconstruction in this thesis, one would argue that the NdFeB supply chain was a complex system at the beginning of the crisis, with many of its actors only dimly aware – if at all – of what was going on elsewhere in the system. The panic buying in late 2010 is a typical example of a positive feedback loop activated because of limited systemic awareness of actors. However, after the crisis the intense scrutiny of the entire supply chain resulted in a much higher level of supply system understanding of the actors involved, thereby removing significantly their earlier myopia. Additionally, one could argue that through vertical integration of actors, both through acquisitions and takeoff agreements, the structure of the system itself has also become less complex.

7.6 Resilience from the actor perspective

The above section discussed the overall outlook of the NdFeB supply chain. We now turn to a discussion of what the results of this research project mean for the actor in the supply chain. This actor-oriented perspective is particularly relevant for supply chain resilience because the benefits of resilience-enhancing measures are often not bestowed on the actors who bear the costs of enhanced resilience. Clearly such unbalance in risks and rewards for individual actors is not helpful to move the system to greater resilience. We will discuss the actors along the NdFeB supply chain, working from the end-product back to the mine (see also Figure 9).

7.6.1 The producer of finished products

Both substitution and recycling are crucially dependent on product design. Implementation of these resilience strategies therefore relies on the producer of the finished product. Furthermore, the use of NdFeB magnets is in principle a good match with novel sustainable business models, such as take-back systems or product-service systems. This is due to the relatively long life-time of a properly sealed NdFeB magnet compared to other components in an average consumer product.

The producer of finished products also has the option of stockpiling REE containing components. However, from an overall supply chain point of view stockpiling makes more sense when done by the smelter operator, who can store rare earths in their powder oxide form instead of as finished components (this will be explained in more detail in the smelter operator section below). The initiative for this type of stockpiling will probably still have to be taken by the finished product producers, as this actor should communicate with the smelter operator to ensure enough stockpile is reserved to cover the time period required for substitution. This requires a direct connection between two actors, which normally are connected only indirectly, via the magnet producer. Additional connections increase the supply chain complexity, which, as we have seen in 4.2.3, can have difficult to predict effects on the stability of the overall system (both negative and positive).

Of all the actors, the producer of the finished NdFeB containing product has the most options for supporting resilience mechanisms, and therefore, arguably, should take the lead in achieving overall supply chain resilience. At minimum, the producer should have a plan for REE substitution and an assessment of implementation time. Both stockpiling and design-for-substitutability can be relatively costly, so a future methodological development would be to calculate the monetary value of resilience and then compare the costs of maintaining a stockpile and designing a highly substitutable product.

7.6.2 The waste manager and recycler

Waste managers face several challenges, such as changing preferences in product design and specification that are not conducive to recycling, strong fluctuations of commodity prices, lack of cohesion and detail in quality standards for recyclable materials, and competition from primary production.

Competition from virgin material is an especially significant barrier. The size of the virgin raw material sector is such that even the largest recycling plants are an order of magnitude smaller than mining sites, while simultaneously having to deal with the fact that waste has a far more complex composition than ore, thus necessitating more unit operations per ton material produced.[9]

Institutionally, the recycling sector is also at a disadvantage. A comprehensive analysis at the EU or Dutch national level is not available, but Johansson et al. compared the governmental support (in the form of direct and indirect subsidies) for the Swedish metals mining and recycling sectors.[1] Their results show that the value added/tonne of metal produced is 114€ for mining and 151€ for recycling, for a similar distribution of metals. One would expect that the Swedish government would therefore support recycling and primary production at least equally. However, they found that mining is subsidized 6.6x higher on a per tonne basis than recycling (2€/tonne versus 0.3€/tonne). They also note that mining is exempt from a landfill tax for their mining waste. If this tax-exemption is also counted as a subsidy, they would receive a massive 737x higher subsidy relative to recycling (221€/tonne). A salient detail is that Swedish subsidies for R&D are 4.5x higher for the mining sector than recycling.[10]

After much consideration we must conclude that the best way forward for the waste management sector is to lobby both at the national and EU level for rules, regulations and subsidies that at minimum provide a level playing field with the mining sector. In a recent report, ISWA recommended that the waste management sector lobby for the following policies (taken directly from the report):[8]

Policies to push recovered materials onto the market (push policies):

- Landfill diversion targets or bans for landfilling of organic waste, recyclable material streams and combustible waste.
- Landfill Tax to encourage alternative treatment options such as energy recovery or recycling.
- Incineration Tax to encourage recycling above incineration.
- Recycling and Recovery targets for specific waste streams.
- Polluter pays policies, such as Extended Producer Responsibility (EPR). Such policies hold producers and importers responsible for the end of life of materials placed on the market and can help to internalize external costs involved in the recovery of secondary raw materials such as those arising from the increased complexity of products.

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[1] Although Sweden is not completely comparable to the Netherlands, it is of interest because it shows how another EU country values its primary and secondary metals sector, and this comparison can be used to argue that the secondary metals market is undervalued by policymakers.

Policies that help to create market demand for secondary materials (pull policies):

- Green taxes (eco-taxes) on consumption and production e.g., taxes on plastic carrying bags, packaging.
- Funds to support environmental performance. e.g. European Commission Eco-Innovation which has one of the aims to encourage the design of innovative products using recycled material and facilitate material recycling.
- Green Public procurement –public authorities to procure goods produced from or with a certain fraction of secondary raw materials.
- Industry target on use of recovered materials in production and manufacturing.
- Innovative fiscal changes to drive behavior change such as reductions in VAT or tax credits for secondary raw materials, recycled products or accelerated depreciation for assets purchased for re-use of recycling of waste materials. Global examples now exist in China, Korea, Mexico and the USA.
- Waste sector engaging in waste prevention and newly emerging circular business models such as where companies offer products as services seeking to retain ownership and internalize benefits of circular resource productivity.

In fact, the EU has very recently (03/12/2015) published its circular economy package, with legislative proposals on waste.[2] Unfortunately the author of this dissertation cannot help but be disappointed in the rather vague and non-committal text contained within. For example:

"As a first step, and under the framework of the Ecodesign directive, the Commission has developed and will propose shortly to Member States mandatory product design and marking requirements to make it easier and safer to dismantle, reuse and recycle electronic displays (e.g. flat computer or television screens)."

Specifically on the recycling of critical materials the CE package has the following to say:

"The Commission is encouraging Member States to promote recycling of critical raw materials in its revised proposals on waste."

Clearly, the ISWA has its work cut out for it.

As a final comment on the role of recycling, despite the extensive attention given to REEs in the scientific and policy literature, the results of this dissertation indicate that, since there seems to be no serious limitation on REE supply from a geological point of view, there is no special moral obligation towards future generations to reduce REE usage, or increase to recycling rates. The environmental benefits of REE recycling – and of REE use in general – should be compared to other options for improving environmental performance through a regular LCA exercise. This also underlines the need to resolve the issues with LCAs for REEs about lack of characterization factors for radioactive and acidic waste (also part of the recommendations for future research).

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[2] http://ec.europa.eu/environment/circular-economy/index_en.htm

7.6.3 The magnet producer

Given the volatility of the NdFeB market, resilience for NdFeB producers is found in product diversification more than anything else. Magnet producers could gain competitive advantage by offering their clients consultancy services on how to design products where one type of magnet is easily substituted for another type, also supplied by said magnet producer. Furthermore, magnet producers can play the vital role in communicating between the stockpile holding smelters and those final product producers that wish to have a stockpile. In this sense they could act as a kind of insurance broker.

7.6.4 The smelter operator

Metallic neodymium is highly susceptible to oxidation, thus the most ideal chemical form for storage is neodymium oxide. Furthermore, there are many different grades of NdFeB magnets, which makes it much more feasible to stockpile the raw material for all of these different grades than to stockpile each grade individually. This puts the smelter operator in a crucial position, because stockpiling of neodymium makes most sense at this step in the supply chain. However, while REEs are usually a small percentage of the overall material costs of a product, for the smelter operator the costs of REOs is very significant. For a product manufacturer a three-month stockpile of REO would not be a significant investment compared to overall business expenditure, while a supply disruption would cause a significant loss of income because the product cannot be made. For the smelter operator on the other hand, the costs of stockpiling are high compared to overall business expenditure, while the benefits to its business are less than for the manufacturer. Arguably, this goes a long way to explaining 2010 situation of insufficient stockpiling.

7.6.5 The REE miner and refiner

Because the extraction process of REEs is highly dependent on the exact mineralogy of the ore, the options of the REE mining and refining actors must be considered together. As discussed in Chapter 3, REE mining and refining need not be unduly burdensome on the environment, but if not done properly it can be. It is often commented that Chinese REE mines are much more environmentally damaging than western counterparts. However, it seems that lack of respect for the environment is pervasive in the mining industry overall. For example, as recently as April 2014 Molycorp was fined in California for violating environmental regulations.[11] The activities of Australian REE miner Lynas in Malaysia are also illuminating. Its REE refining plant (LAMP) was held up significantly over lawsuits regarding the environmental impacts. An NGO commissioned report shows that this was at least partially justified given the seemingly lax attitude of Lynas towards meeting the legitimate concerns of the local population (legitimate considering the fact that a previous REE refinery in the same area had caused massive pollution).[12]

In Chapter 5 we concluded that one of the policy options to improve resilience is the reduction of red tape surrounding the opening of mining sites to reduce the response time to demand increases. The fastest track towards achieving that is for mining actors to take their environmental obligations seriously. One of the main arguments given for the lack of attention to costly environmental measures is that REE prices are on average so low that REE mining would not be profitable when done in an environmentally sound manner. The obvious solution to this is more self-regulation. End-users of REEs could enforce global environmental standards on miners through the use of for example certifications. When every mining actor complies with environmental regulations, this would create a level playing field.

A second recommendation relevant to the mining and refining actors is to support R&D that focuses on expanding the use of those REEs that are co-mined in excess, for example cerium. On the long term this would increase the overall profitability of REE mines.

7.7 Resilience in material supply chains compared to other criticality approaches

The concepts for explaining why crises in material supply chains happen have been subject of study for decades, if not longer (e.g. the classical hog cycle). Recently this work has centered on the concept of material criticality. The first major studies on criticality were mostly based on empirical observations. While this is initially the most obvious approach, it also inherently leads to a type of 'after-the-facts' analysis. This can be seen with REEs, which were recognized as critical only after they had actually become critical. For example Nasser (2015) writes: "Committees of the European Commission (EC 2010, 2014) arbitrarily set a boundary for critical/not critical designation and subsequently classed the rare earths as a group as critical. The US DOE (2010) also imposed a cutoff and then designated Dy, Eu, Tb, Nd, and Y (out of nine REEs examined) as critical." A more complete discussion of recent work on material criticality can be found in Graedel & Reck.[13]

In the remainder of this section we will contrast the criticality approach with resilience, the main difference being that criticality tries to determine what the probability and impact of significant disruptions are, while resilience takes for granted that disruptions (the predictable as well as the unpredictable) will happen eventually and instead focusses on the ways and means by which a supply chain can deal with disruptions. This is perhaps best illustrated by looking at the criticality framework of Graedel et al.[14] as applied to REEs by Nassar et al,[15] who's conclusions are generally in line with the discussion in this chapter, namely that criticality is highly dependent on substitution potential, and that the criticality of REEs is less than found in previous criticality studies.

Nevertheless, significant differences can be found. The main unit of both resilience mechanisms and system disruption as used in Chapter 5 is '% of total market/year'. Although these data are not necessarily easy to find, once available this allows for a consistent comparison across the resilience mechanisms and even different supply chains. In contrast, the criticality framework as developed by Graedel and co-workers uses 16 indicators covering a very wide variety of topics such as Depletion Time, Human Development Index, Substitute Performance, Net Import Reliance Ratio and Global Innovation Index. These indicators are transformed to fit on a 1-100 scale and summed using weighing factors. The result is a three-dimensional graph comparing elements on Supply Risk, Vulnerability to Supply Restrictions and Environmental Implications.

Besides the obvious dissimilarity in breadth and complicatedness resulting from diverging indicator choices, the most salient difference is that the resilience framework is focused on the dynamic aspects of the supply chain; how it changes over time in response to disturbances and incorporating non-linear responses through the explicit use of feedback loops, while Graedel et al. acknowledges that non-linearity plays an important role in complex supply chains, their framework essentially generates a static snap-shot of criticality. This dynamic aspect of supply constraints is incredibly important, and therefore we would go so far as to hypothesize that one can define the criticality of a material in terms of how resilient its supply chain is.

On a perhaps more philosophical note, both the reliance on weighing factors and the widely disparate set of indicators are problematic, because they show an underlying assumption of how the world works, or should work, rather than being based on a 'neutral' theoretical framework (i.e. complex adaptive systems theory). For example, the Graedel framework uses the human development index and environmental impact as an indicator for criticality, which, based on experience with conflict minerals and rare earth elements, seems to be as much wishful thinking as actually of relevance when assessing the supply of these materials to the market.

7.8 Recommendations for future research

The fact that rare earth metals are dominantly mined in China and that Chinese mining is not properly covered by statistics and verified environmental modelling makes for a scarcity of data – both economic and environmental. One aspect is that neither the LCA presented in Chapter 3, nor other LCAs on REEs[16-19] address the issue of radioactive waste connected to rare earth production. This is due to a combination of uncertain data and a lack of appropriate characterization factors. Along the same lines, the characterization factor for hydrogen fluoride carries an order of magnitude uncertainty, and factors for emissions of acids into water, and waste treatment of REE processing are not available at all. Current LCA results therefore probably significantly underestimate the true environmental impact of REE processing. It is recommended to implement or refine these characterization factors.

In closing, resilience in industrial ecology is an exciting topic, and there are quite a lot of avenues of future research. On the one hand the resilience framework presented in this dissertation can be broadened via application to case studies other than NdFeB. On the other hand the framework can be deepened by connecting resilience to methods generally used in the IE community, such as input-output modeling, substance flow analysis, mass flow analysis and life cycle assessment. Resilience is a popular topic in the supply chain research field, so a connection to that field would be of interest. In Chapter 6 quantification of resilience was done through data collected from interviews and literature sources. This quantification could be improved upon by drawing on more data sources such as trade statistics, as for example was done in Mancheri,[20] and implementing the dynamic model for the resilience system that is shown in a qualitative form in Chapter 5. In order to test hypotheses about how various resilience mechanisms could be implemented and optimized various kinds of modeling should be employed. Using an agent based modeling (ABM) approach seems like a natural fit for investigating resilience from an emergent system property perspective, and could build upon the work of Riddle et al., who built an ABM of the Nd and Dy supply chains to explore possible future supply and demand trajectories.[21] A network analysis based approach can be used to investigate interactions between different supply chains and could be based on databases such as EXIOBASE or ecoinvent.

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