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CHALLENGES FOR SUSTAINABILITY IN CRITICAL RAW MATERIAL ASSESSMENTS

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ABSTRACT

The commonly-used methodologies for raw material criticality assessments produce lists based on economic parameters. However, they do not provide qualitative guidance or recommendations as to how to reduce criticality. Paradoxically, publishing these lists impacts the system in a way that can make critical resources become even more critical, because markets may react by increasing prices for critical raw materials, and conflict for these resources may increase. We propose a complementary methodology, System Dynamics Modelling, which provides better guidance for policy makers because of its insights into the driving forces behind the criticality of raw materials. Also, this methodology allows us to take into account the biophysical limits and the social dynamics which underpin the system, and thus enables us to understand the context in which raw materials become critical. The clarification of the drivers of criticality of raw materials, provided by our research method, can enhance the recommendations and guidance for policy- and decision-makers to respond to warning signals in their management. The applicability of our approach is illustrated by two case studies, on phosphorus and indium. We conclude that the externalities (social and environmental) of raw material extraction, both for production and consumption, should be considered by policy makers in order to account for the true cost of critical raw materials.

Contribution/Originality: This study contributes in the existing literature on critical raw materials. It uses logical methodology – system dynamics (CLD) – to understand social and economic drivers for phosphore and Indium. This methodology could be helpful for the economists who work on Economy of natural resources or Economy of Environment.

1. INTRODUCTION

Raw materials are crucial to the world economy and essential to maintaining our welfare. They underpin industry and support the modern technology we use daily, such as smartphones, computers, and the harvest of the green economy. Securing reliable and unhindered access to certain raw materials is a growing concern for both developed and developing countries. To address this challenge, many countries and international institutions have created a list of Critical Raw Materials (CRMs) or commissioned a predictive analysis of future metal demand to support the transition to a low carbon future (IEA, 2015; World Bank, 2016).

Historically, the concept of critical raw materials has mainly been developed by government agencies and has been triggered by concerns over supply shortages or market price spikes in crisis years. For example, at the end of the first World War the United States (US) developed a "Harbord list" with materials "that had presented wartime supply difficulties" (Haglund, 1984). Later, in 1939 and 1944, this list was further divided into critical and strategic materials by the US Army and Navy munitions board, Haglund (1984). During the Cold War US interests in critical raw materials intensified, and the definition of critical raw materials was revisited in 1979 by the US Strategic and Critical Materials Stock Piling Act (Haglund, 1984). More recently, the economic crisis of 2007-2008 led to the development of several government reports (National Research Council, 2008; European Commission, 2010). Since the 2008/9 economic crisis, an increasing number of scientists have studied the issue of raw material criticality and published their findings in academic journals (Rosenau-Tornow *et al.*, 2009; Senk *et al.*, 2012; Massari and Ruberti, 2013).

There is currently no agreed definition of a critical raw material. The reasons for this is that criticality is often thought of, or evaluated, from different perspectives, e.g. a national or regional perspective versus a company perspective versus a technology or product perspective (Chakhmouradian *et al.*, 2015; Malinauskienė *et al.*, 2016). The European Commission (EC) definition of 2010 considers that to be considered as critical: "*a raw material must face high risks with regard to access to it, i.e. high supply risks or high environmental risks, and be of high economic importance. In such a case, the likelihood that impediments to access occur is relatively high and impacts for the whole EU economy would be relatively significant.*"

The standard way of assessing the criticality of materials is by using a criticality matrix, in which materials are located as dots between two axes (Erdmann and Graedel, 2011). The meaning of these two axes, or dimensions, of criticality is derived from basic risk analysis: (1) the probability of a disruption in the resource supply, termed 'supply risk', (2) the impact caused by such a constraint, termed 'vulnerability' (Stafford Lloyd MEng and EngD, 2012; Habib and Wenzel, 2016). The overall risk, or criticality, is the product of these 2 dimensions, and creates hyperbolic contours of constant criticality in the plot, allowing for comparison of criticality between different raw materials, as shown in Figure 1 (Glöser-Chahoud *et al.*, 2016).

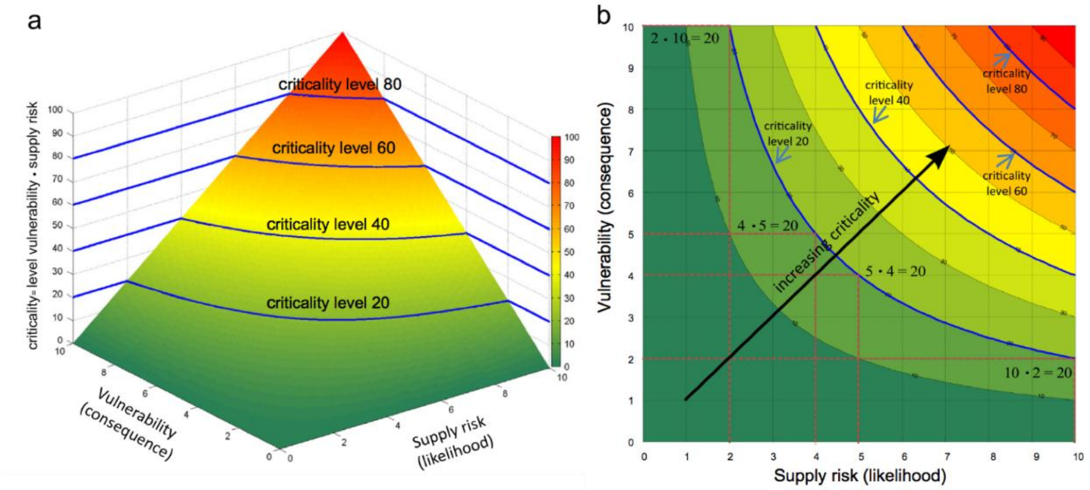


Figure-1. Material criticality matrix based on basic risk theory

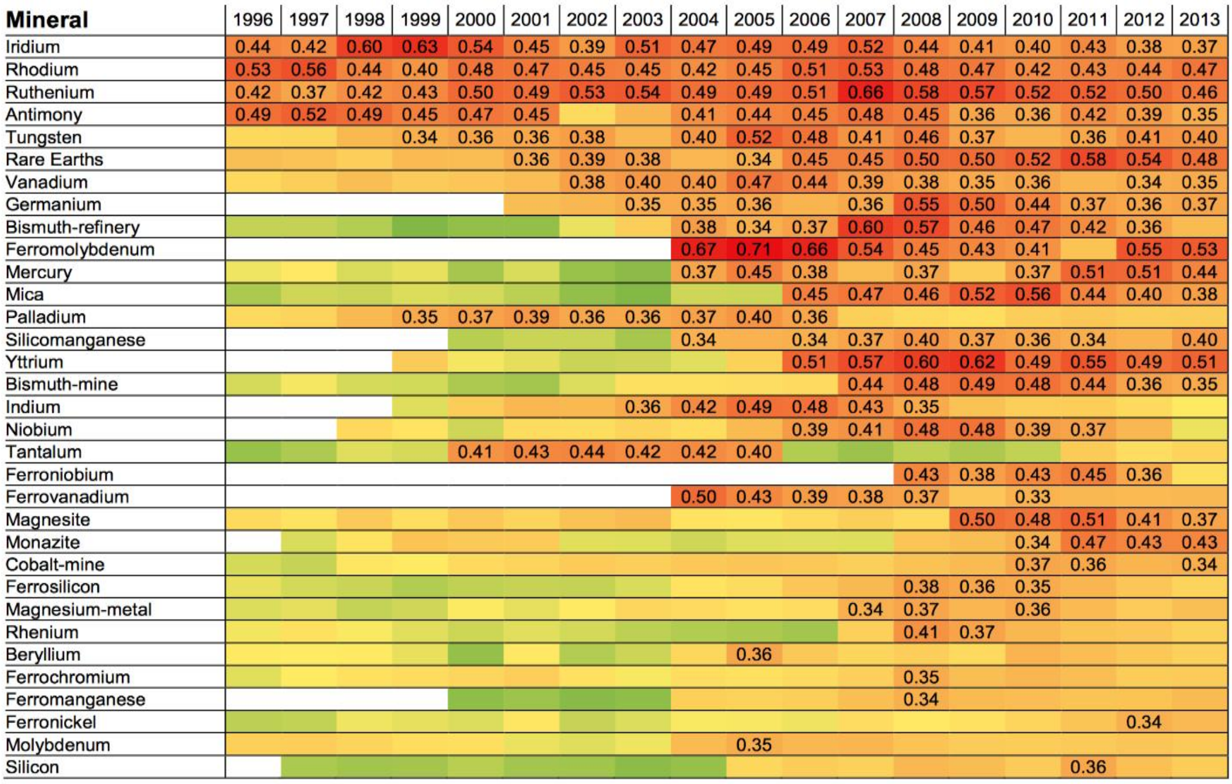
Source: Glöser *et al.* (2015)

However, these axes are often modified so much that the connection with risk theory is lost (Helbig *et al.*, 2016; Frenzel *et al.*, 2017) for instance by changing the terminology and indicators of the axes (Dewulf *et al.*, 2016; Helbig *et al.*, 2016) or by adding or omitting an axis (Frenzel *et al.*, 2017). This leads to significant differences in the findings on the criticality of a material between different assessments. In 2013 and 2016, US/Japan/EU trilateral workshops on CRMs were organized to exchange information on the upcoming reviews of the critical raw materials list, to discuss progress, and to compare analysis and data on critical raw materials (EC, 2014). The different approaches to CRM assessments by US government agencies, Japan's mineral policy, the European Commission Raw Materials Strategy, and the World Bank's CRM research activity are summarized below.

In the US, there is no single critical materials policy or strategy. Different government agencies represent differing interests (King, 2013). The main players are the Department of Energy, that finances the Critical Materials Institute, which is concerned with the supply of materials needed for clean energy technology; the Department of the Interior that has the responsibility for the US Geological Survey; and the Department of Defense. At the White House, the National Science and Technology Council (NSTC) has established a Subcommittee on Critical and Strategic Mineral Supply Chains that co-ordinates the critical materials activities.

With regard to critical solid minerals, a variety of legislation is being considered in Congress. Both the Senate and the House are looking at legislation that would result in the setting up of a national list of critical materials. They have also addressed the simplification of the mining permit processes that are perceived to delay the establishment of new sources of critical materials. Also they are discussing the encouragement of recycling, workforce development, international collaborations, and actions on specific elements, e.g. lead. It has been underlined that materials criticality is affecting the US now, while solutions (development of mines or substitute materials) may take up to 20 years to take effect. In 2013, shortages of europium (Eu) and terbium (Tb) delayed the transition to high-output T5 fluorescent lamps in buildings, thereby preventing energy savings of around 50% in lighting. Also, shortages in neodymium (Ny) and dysprosium (Dy) needed for high-strength magnets prevented the replacement of wind turbine gearboxes (the dominant cause of downtime) by direct-drive units (King, 2013).

Table-1. Screening of Minerals on "potential criticality" based on a threshold C indicator value of 0.335 during at least one year.



Mineral	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Iridium	0.44	0.42	0.60	0.63	0.54	0.45	0.39	0.51	0.47	0.49	0.49	0.52	0.44	0.41	0.40	0.43	0.38	0.37
Rhodium	0.53	0.56	0.44	0.40	0.48	0.47	0.45	0.45	0.42	0.45	0.51	0.53	0.48	0.47	0.42	0.43	0.44	0.47
Ruthenium	0.42	0.37	0.42	0.43	0.50	0.49	0.53	0.54	0.49	0.49	0.51	0.66	0.58	0.57	0.52	0.52	0.50	0.46
Antimony	0.49	0.52	0.49	0.45	0.47	0.45			0.41	0.44	0.45	0.48	0.45	0.36	0.36	0.42	0.39	0.35
Tungsten				0.34	0.36	0.36	0.38		0.40	0.52	0.48	0.41	0.46	0.37		0.36	0.41	0.40
Rare Earths						0.36	0.39	0.38		0.34	0.45	0.45	0.50	0.50	0.52	0.58	0.54	0.48
Vanadium							0.38	0.40	0.40	0.47	0.44	0.39	0.38	0.35	0.36		0.34	0.35
Germanium								0.35	0.35	0.36		0.36	0.55	0.50	0.44	0.37	0.36	0.37
Bismuth-refinery									0.38	0.34	0.37	0.60	0.57	0.46	0.47	0.42	0.36	
Ferromolybdenum									0.67	0.71	0.66	0.54	0.45	0.43	0.41		0.55	0.53
Mercury									0.37	0.45	0.38		0.37		0.37	0.51	0.51	0.44
Mica											0.45	0.47	0.46	0.52	0.56	0.44	0.40	0.38
Palladium				0.35	0.37	0.39	0.36	0.36	0.37	0.40	0.36							
Silicomanganese									0.34		0.34	0.37	0.40	0.37	0.36	0.34		0.40
Yttrium											0.51	0.57	0.60	0.62	0.49	0.55	0.49	0.51
Bismuth-mine												0.44	0.48	0.49	0.48	0.44	0.36	0.35
Indium								0.36	0.42	0.49	0.48	0.43	0.35					
Niobium											0.39	0.41	0.48	0.48	0.39	0.37		
Tantalum					0.41	0.43	0.44	0.42	0.42	0.40								
Ferroniobium													0.43	0.38	0.43	0.45	0.36	
Ferrovanadium									0.50	0.43	0.39	0.38	0.37		0.33			
Magnesite														0.50	0.48	0.51	0.41	0.37
Monazite															0.34	0.47	0.43	0.43
Cobalt-mine															0.37	0.36		0.34
Ferrosilicon													0.38	0.36	0.35			
Magnesium-metal												0.34	0.37		0.36			
Rhenium													0.41	0.37				
Beryllium										0.36								
Ferrochromium													0.35					
Ferromanganese													0.34					
Ferronickel																	0.34	
Molybdenum										0.35								
Silicon																0.36		

Source: NSTC (2016)

The criticality assessment methodology of the National Science and Technology Council (NSTC) (2016) introduces a compound criticality indicator, C, as an early-warning screening for each mineral studied, on a 0 to 1 scale. C is the geometric mean of 3 indicators: supply risk (R), production growth (G), and market dynamics (M). These 3 indicators present complementary aspects of availability: "R is a measure of the risk associated with geopolitical production concentration, G incorporates changes in the mineral's market size and reliance on geological resources, and M tracks the mineral's price sensitivity to changes in its market." NSTC (2016) A cluster-analysis considers a mineral to be considered "potentially critical" if C is above 0.335. For 2013, 17 minerals were identified as potentially critical: ferromolybdenum (FeMo), yttrium (Y), (La-Lu), rhodium (Rh), ruthenium (Ru), mercury (Hg), monazite, tungsten (W), silicomanganese (SiMn), mica, iridium (Ir), magnesite, germanium (Ge), vanadium (V), bismuth mine production (Bi), antimony (Sb), and cobalt mine production (Co). In a second stage, these minerals identified as potentially critical were studied in-depth to understand the drivers of their criticality and which of them poses a significant risk to US economic and national security interests.

In Japan, mineral policy is driven by the Ministry of Economy, Trade, and Industry METI) (Morita, 2013). Within the METI, which has 9 bureaux and 3 agencies, 2 bureaux and 1 agency deal with Japan's minerals policy. The first bureau is the Industrial Science and Technology Policy and Environment Bureau in charge of technology development, which includes the division for the Promotion of Recycling. The second one is the Manufacturing Industries Bureau, which is in charge of industrial promotion to strengthen Japanese industry, and which includes the Nonferrous Metals division, in charge of non-ferrous industries in Japan. The third government function is covered by the Agency for Natural Resources and Energy. This agency has the Mineral and Natural Resources division to which the Japan Oil, Gas and Metals National Corporation (JOGMEC) belongs.

METI ensures the supply of natural resources to Japan, and conducts an annual material flow survey on various raw materials including base metals and rare metals. The survey provides material flow diagrams for both national and world-wide supply, demand trends, export and import trends, and on the share of recycled (secondary) products in the domestic consumption.

In Japan 3 main strategies have been applied to secure natural resource supplies: - 1. Since 2009, the Strategy for Securing Rare Metals has focused on policy measures to ensure the supply of strategic materials. Strategic materials are chosen based on the stability of supply, e.g. supply and demand trends, trends in developing mines, or misdistribution of resources, 2. Since 2010 the Energy Base Plan has set numeric targets to increase the metal supply from mines and recycling. Base metals (aluminum, copper, iron, lead, tin, and zinc) are targeted to increase from 40 % to over 80 % by 2030. Strategic rare metals are targeted to increase from 0 % to over 50 %, 3. Since 2012 the Strategy for Securing Natural Resources has identified "Strategic Mineral Resources" to focus policy measures on their supply. Not only for rare metals, but also for base metals, due to concerns about rapidly increasing demand in emerging countries, and non-metal materials, which are essential for industry, are also considered. 30 minerals were designated "strategic minerals". Strategic minerals were selected against a background of their growing importance in industry and rising supply risk, which resulted in the designation of minor metals such as indium, platinum, rare-earth elements (REEs), and common metals such as iron, copper, and lead. The strategy aims at a stable supply of these metals via 4 pillars: - (i) acquisition of mineral interests, (ii) recycling from industrial processes and end-of-life products, (iii) developing substitution materials, (iv) stockpiling. Two of the criteria for definition of strategic minerals - supply risk and vulnerability of industrial activities to supply restriction - correspond to the concept of "criticality" of materials.

Before the 2009 Strategy for strategic minerals, Japan's criticality assessment was reported by the New Energy and Industrial Technology Development Organization (NEDO). The NEDO assessment designated elements considered to be at risk of resource securement problems as "important minerals", which were identified by evaluating 5 risk categories with 12 components. Although the assessment report did not use the terms "criticality" or "critical material", the assessment evaluated the critical metals for Japan. In the NEDO assessment, the 12 components were evaluated for 39 minor metals in 2008.

Table-2. Criticality components used in the NEDO assessment

Category	Component
Supply risk	Depletion time Concentration of reserves Concentration of ore production Concentration of import trading partners
Price risk	Price change Price variation
Demand risk	Mine production change Domestic demand growth Domestic demand growth for specific uses
Recycling restriction	Stockpiles Recyclability
Potential risk	Possibility of usage restrictions

Source: NEDO (2009)

The results were then aggregated into single criticality scores. The NEDO assessment designated 14 of 39 metals with high criticality scores as important minerals. For each of the 12 components, scores representing their securement importance were designated with 0, 1, 2, or 3 points. For "depletion time", for example, 3 was given to metals with less than 50 years of depletion time; 2 for 50-100 years; 1 for 100-150 years; 0 for over 150 years. For "stockpiles", metals with stockpiles built up through governmental policy were evaluated as 0, and 1 for other metals. The scores for the 12 components were aggregated into a single criticality score using weighting factors. The factors used in the NEDO assessment were 25% of the aggregated score for supply risk, price risk, and demand risk, 20% for recycling restriction, and 5% for potential risk. The weighting among components within each risk category were equal (?). Finally, comprehensive criticality scores were calculated with a maximum of 32 points possible for each of 39 metals. Metals with 18 points or higher were regarded as important minerals (Hatayama and Tahara, 2015).

The European Commission (EC) regards Critical Raw Materials as economically important raw materials which are subject to a high risk of supply interruption (EASAC, 2016). In this respect, the EC launched the Raw Materials Initiative (RMI) in 2008 which established an integrated strategy to respond to the different challenges related to access to non-energy and non-agricultural raw materials. The RMI is based on three pillars: 1. Ensuring a level playing field in access to resources in third party countries, 2. Fostering a sustainable supply of raw materials from European sources, 3. Boosting resource efficiency and promoting recycling.

For the EC, the initial steps (EC, 2008) were to identify critical materials on the basis of 'supply risk' and an 'environmental country risk' - where producing countries might place regulations on the supply of raw materials to Europe to reduce their environmental impact.

In 2010, the EC (2010) introduced a methodology to identify raw materials deemed critical to the EU, with 3 dimensions: a) the "economic importance" of the material - breaking down its main uses and attributing to each of them the value added of the economic sector that has this raw material as an input; b) the "supply risk" - taking into account the political/economic stability of the producing countries, the level of concentration of production, the potential for substitution, and the recycling rate; and c) the "environmental country risk" - assessing the risk that measures might be taken by countries with weak environmental performance in order to protect their environment and, in doing so, endanger the supply of raw materials to the EU. Inclusion of this third environmental dimension is said not to change the results compared to an assessment based only on the 2 primary dimensions: *economic importance* and *supply risk*. Further, changes in the geopolitical/economic situation are regarded as having much more impact on criticality within the considered time horizon (10 years) than geological availability, which is not included in the indicators, partly because of the lack of reliable indicators of long term geological availability. 41 materials were assessed for criticality and 14 initially identified as critical, representing a first EU list of CRMs in 2011. These were antimony (Sb), beryllium (Be), fluorspar, graphite, germanium (Ge), indium (In), magnesium (Mg), rare earth elements (REEs), tungsten (W), cobalt (Co), tantalum (Ta), platinum group metals (PGMs), niobium (Nb) and gallium (Ga). Subsequently, the EC recommended *"policy actions to ensure that recycling of raw materials and products containing them becomes more efficient through promoting collections, stopping illegal exports of end of life (EoL) products and promoting research on system optimization and on tackling technical challenges"* (EC 2010, page 3).

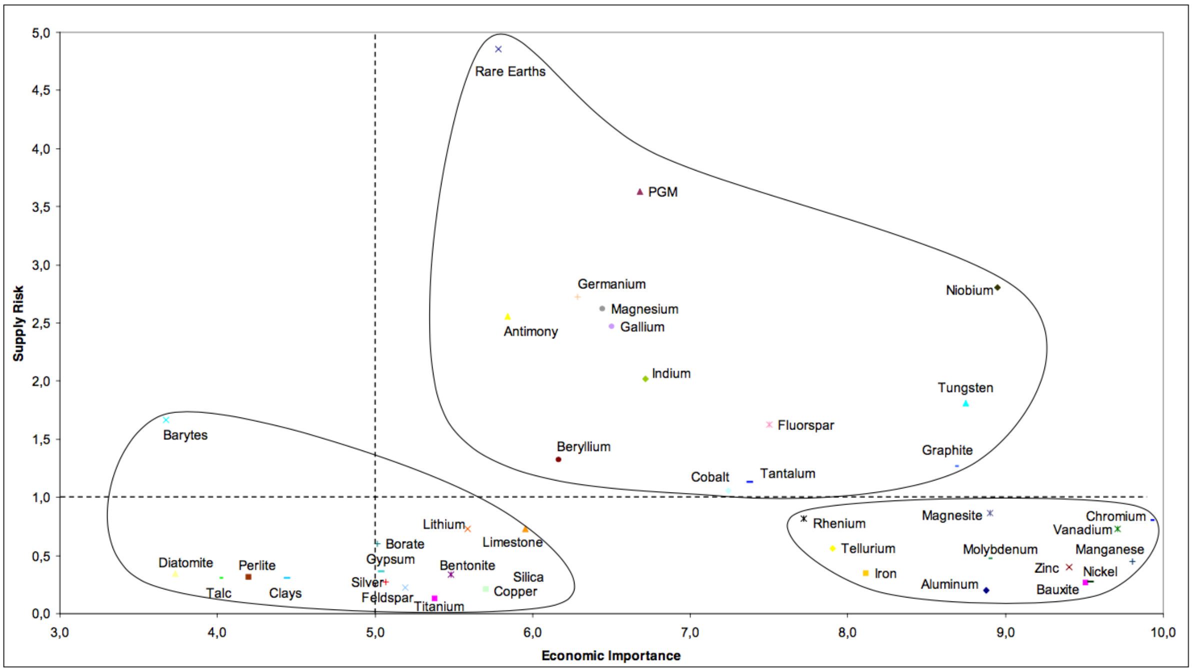
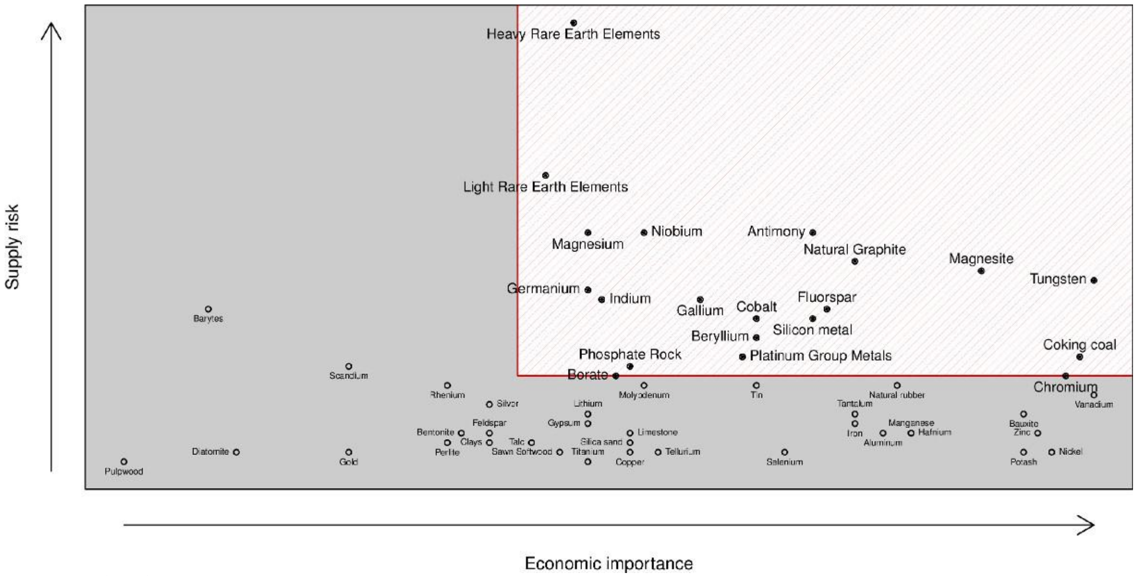


Figure-2. First EC list of Critical Raw Material, 2010

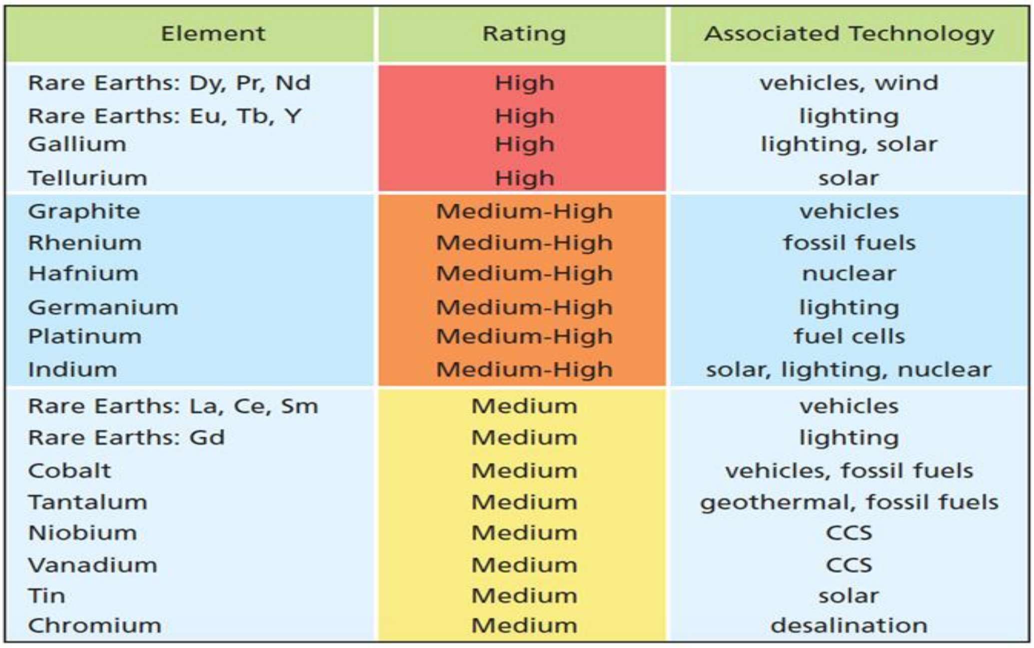
Source: EC (2010)



Source: EC (2011)

In parallel, the EC charged the Joint Research Centre (JRC) with investigating potential bottlenecks associated with the use of metals in 6 energy technologies: nuclear, solar, wind, bio-energy, carbon capture and storage, and electricity grids Moss *et al.* (2013). The JRC assessed criticality against the risk criteria of supply constraints, demand growth rate, political risk, and geographical concentration, and summarized the most critical elements in the following table.

Table-3. Critical elements and associated technologies



Element	Rating	Associated Technology
Rare Earths: Dy, Pr, Nd	High	vehicles, wind
Rare Earths: Eu, Tb, Y	High	lighting
Gallium	High	lighting, solar
Tellurium	High	solar
Graphite	Medium-High	vehicles
Rhenium	Medium-High	fossil fuels
Hafnium	Medium-High	nuclear
Germanium	Medium-High	lighting
Platinum	Medium-High	fuel cells
Indium	Medium-High	solar, lighting, nuclear
Rare Earths: La, Ce, Sm	Medium	vehicles
Rare Earths: Gd	Medium	lighting
Cobalt	Medium	vehicles, fossil fuels
Tantalum	Medium	geothermal, fossil fuels
Niobium	Medium	CCS
Vanadium	Medium	CCS
Tin	Medium	solar
Chromium	Medium	desalination

Source: JRC (2013)

In 2014, the EC updated its list of critical raw materials. After analyzing 54 materials with the criteria of economic importance and supply risk, 20 CRMs were in the criticality zone of economic importance and high supply risk. These CRMs were antimony, beryllium, borates, chromium, cobalt, coking coal, fluorspar, gallium, germanium, indium, magnesite, magnesium, natural graphite, niobium, PGMs, phosphate rock, REEs (heavy), REES (light), silicon metal and tungsten. In 2015, the third pillar in Box 1 was included in the circular economy approach in the Commission's package (EC, 2015).

In 2017, the EC published a new list for which the methodology had been improved by the JRC (2016). It covers a larger number of materials screened: 78 materials or 61 raw materials, consisting of 58 individual and 3 grouped materials (compared to 54 in 2012 and 41 in 2011). The methodology remains largely the same, focusing on supply risk (SR) and economic importance (EI) as the main dimensions of criticality, to ensure comparability with previous assessments. Updates to the methodology include: taking a supply chain perspective by identifying the most critical points in the raw material production stages, inclusion of substitution potential of materials in EI in supplement to SR, more specific allocation of raw materials to the relevant end-use applications and corresponding manufacturing sectors to increase the accuracy of EI calculations, inclusion of import reliance for SR by considering the shares of import vs. domestic sourcing of the global supply, and inclusion of trade-related parameters based on export restrictions and EU trade agreements. Of the 61 materials screened, the following 26 were identified as critical: Antimony, Baryte, Beryllium, Bismuth, Borate, Cobalt, Fluorspar, Gallium, Germanium, Hafnium, Helium, HREEs, Indium, LREEs, Magnesium, Natural graphite, Natural Rubber, Niobium, PGMs, Phosphate rock, Phosphorus, Scandium, Silicon metal, Tantalum, Tungsten, and Vanadium (EC, 2017).

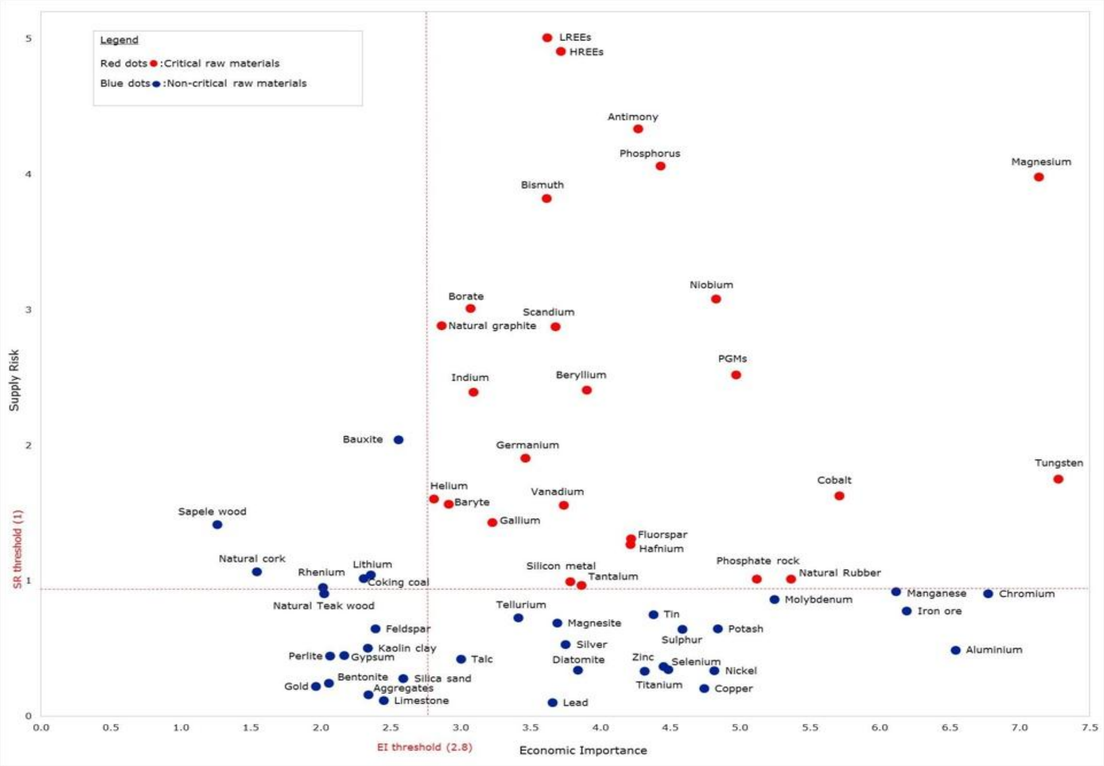


Figure-3. Third list of Critical Raw Material from EC (2017)

Source: EC (2017)

The World Bank (WB), in 2016, in collaboration with the International Council on Mining and Metals (ICMM) tackled the CRM question for green energy technology with a different methodology than the ones described above. The WB modelled projections of future demand for mining and metals for a low carbon future, applying the Energy Technology Perspective (ETP) scenarios developed by the International Energy Agency (IEA). "The metal use per unit of installed capacity was multiplied by the projected yearly capacity installation for each energy technology under consideration." Adding these calculations to the IEA's Energy Technology Perspective scenarios, the annual demand between 2007 and 2050 was projected for a particular metal in a particular energy technology. They identified copper, silver, aluminium (bauxite), nickel, zinc, and possibly platinum, among others, as key base metals and neodymium and indium[1] among others, as key rare earth metals for the transition to a low carbon future. Although they admit that "the actual metals that will experience dramatic increases is unclear and extremely difficult to predict." (WB, 2017).

Considering these studies and reports (US, Japan, EC, and WB), there are some limits to their definitions and methods for assessing the criticality of raw materials. Firstly, they identify CRMs from an exclusively macro-economic perspective, only defining or assessing materials as critical if a supply disruption would be harmful to their economies. Other values of the raw materials, such as socio-cultural and life-support functions are not represented by criticality. Secondly, although the concept of criticality is a dynamic state of a material evolving continuously depending on socio-economic conditions, these assessments only provide analyses of a snapshot in time. A more dynamic approach, providing the possibility of analyzing trends through time by resource, is argued for by Glöser and Faulstich (2012) linking the methods of System Dynamics with the Criticality Matrix. Thirdly, it can be argued that by forcing multiple and diverse indicators into the 2 dimension of criticality matrices, the overview of what is actually driving the criticality situation is lost (Jin *et al.*, 2016) which in reality is the most valuable information to develop policy recommendations for decision-makers.

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[1] See Stamp, Wäger and Hellweg (2014) for linking energy scenarios between indium and CIGS solar cells.

So, in this article, we propose the use of System Dynamics and Scenario Planning to analyse raw material criticality, which enables us (1) to consider a sustainability perspective rather than one based solely on economic concerns, (2) to demonstrate the benefits of a dynamic approach, and (3) to present a tool which can help to identify the drivers of the criticality level of a certain raw materials. We use two case studies, on phosphorus and indium, to test our approach.

2. METHODOLOGICAL FRAMEWORK

The methodological framework of this paper is based on System Dynamics.

System Dynamics was developed at MIT during the 1950s by J.J Forrester. For Forrester (1961) industrial dynamics was a way of studying the behavior of industrial systems to show how policies, decisions, structures and delays are interrelated in influencing growth and stability. To speak of systems "*implies a structure of interacting functions. Both the separate functions and the interrelationships as defined by the structure contribute to the system behavior*" (Forrester, 1967).

System Dynamics help us "*to learn about dynamic complexity, understand the sources of policy resistance and design more effective policies*" (Sterman, 2000). As an interdisciplinary method, System Dynamics has its roots in the theory of nonlinear dynamics and feedback control developed in mathematics, physics, and engineering (Milsum, 1968; Wolstenholme and Coyle, 1983; Wolstenholme, 1985). Because it can be applied to understand the behavior of human as well as physical and technical systems, system dynamics has also been used in Social Sciences and Economics.

The system dynamics approach has 4 hierarchies of structure (Coelho *et al.*, 2017): (1) Closed boundary around the system, (2) Feedback loops as the basic structural elements within the boundary, (3) Level (state) variables representing accumulations within the feedback loops, (4) Rate (flow) variables representing activity within the feedback loops.

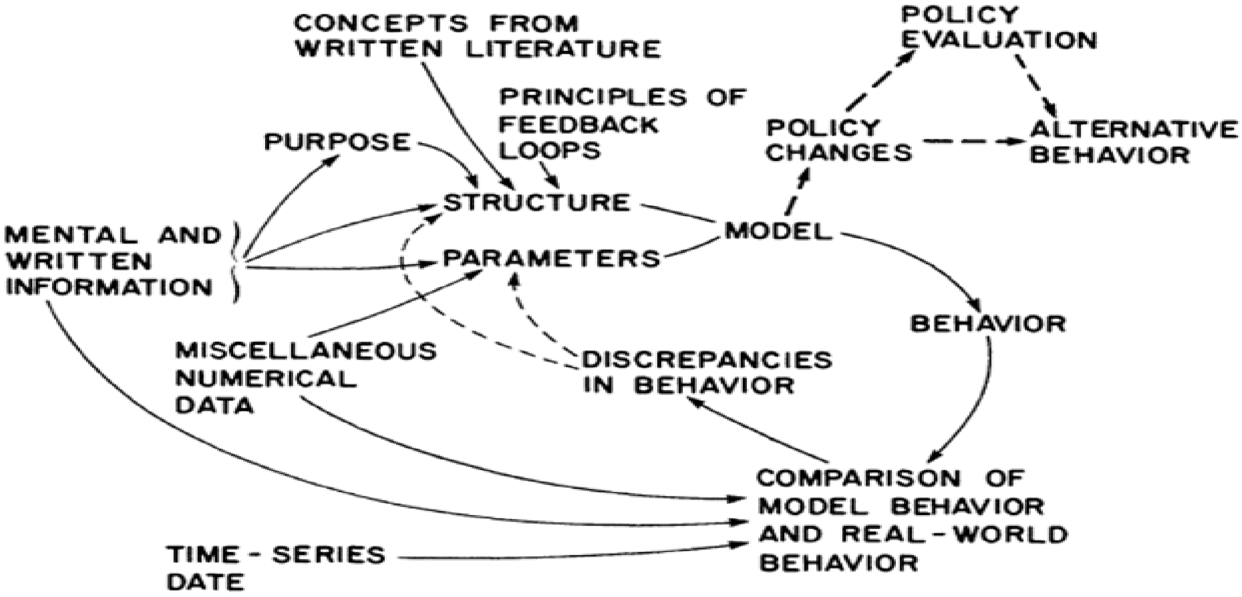

Figure-4. Creating a System Dynamics Model

Source: Forrester (1975)

Closed System boundary: To develop a complete concept of a system, the boundary must be established within which the system interactions that give the system its characteristic behavior take place.

Feedback loop structure: The dynamic behavior of systems is generated within feedback loops (Roberts, 1975). A feedback loop is composed of two kinds of variables, called rate and level variables. A feedback loop is a structure within which a decision point, the rate equation, controls a flow or action stream. The action is integrated to generate a system level. Information about the level is the basis on which the flow rate is controlled.

Table-4. Four steps in the theory of system structure

A Closed boundary		
1 Feedback loops		
	a Levels b Rates	
		(1) Goal (2) Observed condition (3) Discrepancy (4) Desired action

Source: Forrester (1967)

In a system dynamics model, the polarity of each feedback loop is a crucial part of understanding the model's behavior. The perturbation of a loop may result in the magnification of the original effect; this unstable response is known as a positive feedback loop polarity (a reinforcing loop). Alternatively, a perturbation may be counteracted, or resisted by the operation of the loop. This equilibrating response is known as a negative feedback loop polarity (a balancing loop).

Two diagram methods are dominant in the system dynamics community. Broad representations of the variables and the feedback structure of a model are conveyed using Causal Loop Diagrams (CLD). In contrast, stock/flow diagrams (SFD) are more detailed, differentiating between state and flow variables.

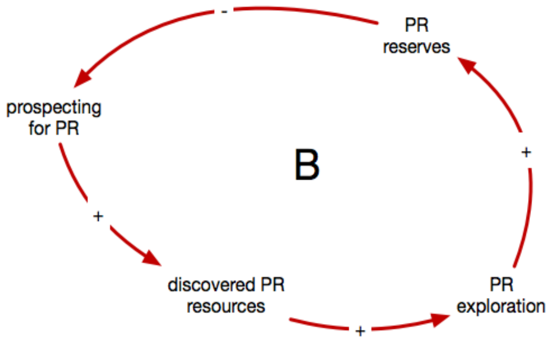

Figure-5a. Balancing Loop for Phosphate

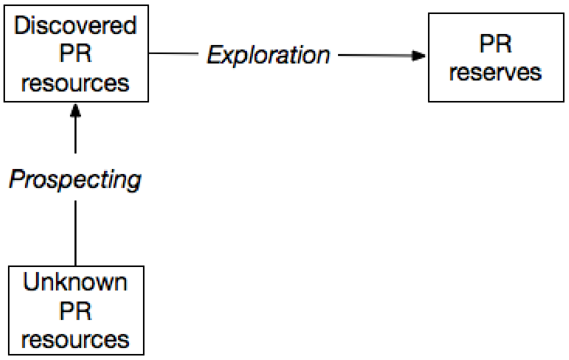

Figure-5b. Flowchart representation of the CLD

For instance, Figure 5a shows a balancing loop describing the interaction between prospecting for phosphate rock (PR) and PR reserves. The more we prospect for PR, the more PR resources we find. This is shown with a positive causality (+), as a change in the first variable will lead to a change in the same direction for the second variable. Next, the more discovered PR resources we have, the more we explore with the purpose of exploitation – this is another positive interaction. The more we explore, the more PR reserves to exploit we will have. However, the more PR reserves to exploit we have, the less we will be inclined to invest in further prospecting. Thus, a positive change in PR reserves leads to a negative change in prospecting for PR. This is a negative causality. Overall, if we start with a positive change in prospecting for PR, we will end up with a negative causality on the same variable – it means this loop is balancing. If hypothetically having more PR reserves led to more prospecting for PR, then this loop would have been reinforcing: a positive change in prospecting for PR would have concluded with more positive signals coming from the PR reserves and vice versa. Figure 5b shows the flowchart representation of the CLD, how PR moves from stocks (squares) through flows (arrows). The unknown PR resources stock moves through prospecting to the discovered PR resources, which ultimately reach the PR reserve stock by means of exploration.

3. ECONOMIC DYNAMICS OF CRITICAL RAW MATERIALS

Natural resources are often associated with goods that are storable but not reproducible. The impossibility of reproducing these goods (apart from a discovery of new deposits) has led economists to insist on the following two points: on the one hand, stocks (more precisely reserves) are considered to be given, and on the other hand, there is a close link between the rate of extraction and sales of natural resources. If the rate of extraction can be equated with sales, since substitution of production is impossible, the company in charge of mining operations may seek to either accelerate extraction (i.e. substitute current sales for future sales) or slow it down (i.e. substitute future sales for current sales). A company would thus be able to influence the price of natural resources by varying its sales by modifying the extraction rate.

The relation between price and extraction rate for a natural resource was introduced by Hotelling (1931) in his article "*The Economics of Exhaustible Resources*" by making a parallel between safeguarding the intergenerational heritage and the influence of monopolies: « *The conservation movement, in so far as it aims at absolute prohibitions rather than taxation or regulation in the interest of efficiency, may be accused of playing into the hands of those who are interested in maintaining high price for the sake of their own pockets rather than of posterity*» (1931, p. 1937 – 1938).

Hotelling assumes[2] that owners of a natural resource always want to maximize the present value of their future profits.

In perfect competition, the owners of a mine are indifferent between receiving now a price p_0 for a unit of its product or receiving a price p_0e^{it} after a time t, so the price can be expected to be a function over time of the form:

$p_t = p_0e^{it}$ (1)

Hotelling takes the price to be the net price after paying the cost of extraction and placing upon the market: "Here p is to be interpreted as the net price received after paying the cost of extraction and placing upon the market"(1931, p 141). Under these conditions, if interest rates (what Hotelling calls "*the degrees of impatience*") vary among mine owners, this will also affect the extraction rate.

When the price P_t is set, the different units of the resource will have the same (discounted) value at any point in time and the mine owner will not seek to change the extraction rate from one period to another, that is $p_0 = p_te^{-it}$. The value of p_0 will depend on the demand and the total available quantity of the resource (noted A). Considering that q = f (p, t) is the quantity taken at time t if the price is *p*, we have the following equation:

$$\int_0^T q\,dt = \int_0^T f\,(p_0\,e^{i\,t}, t\,)\,dt = A \qquad (2)$$

At T, the final extraction date, the requested quantity decreases and approaches 0, the equation becomes $\int(p_0e^{it}, T) = 0$.

Therefore, as Hotelling points out, the net price will change in line with changes in interest rates[3], whose determinants are independent of the product in question, of the industry concerned, and of changes in mining production: « *The market rate of interest must be used by an entrepreneur in his calculations ... Of course, changes in this rate are to be anticipated, especially in considering the remote future. If we look ahead to a distant time when all the resources of the earth will be near exhaustion, and the human race reduced to complete poverty, we may expect very high interest rates indeed*» (1931, p. 144).

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[2] Omerani (1991) recalls that Hotelling's basic assumption is that the initial stock as well as the present and future conditions of extraction of this stock are certain.

[3] Solow (1974) has highlighted the Hotelling's rule based on the financial asset market. For example, a mine owner is only interested in leaving a deposit of resources in the ground if the latter is appreciated in value. On the other hand, asset markets can only be balanced when all assets in a certain risk class have the same rate of return. Thus, at equilibrium, the value of a deposit of resources in the soil must grow at a rate equal to the interest rate.

In the case of a monopoly, Hotelling argues that a company can influence the price by varying its extraction rate (i.e. sales). The company will seek to maximize the present value of its future profits (we have reproduced Hotelling's method of calculating variations) (1931, p. 146-147).

$$\int_0^T pqe^{-it}\,dt \qquad (3)$$

Under the constraint $\int_0^T qdt = A$ (4)

The maximization program can be presented from the Lagrangian

$$L = pq\,e^{-it} + \quad (A-q)\lambda$$

By setting λ = 0, this allows us to fall back on the case of inexhaustible resources (sustainable and reproducible goods).

$$\frac{dL}{dq} = e^{-it}(p + \frac{dp}{dq}q) - \lambda = 0$$

$$\frac{dL}{d\lambda} = A - q$$

Hotelling's rule can then be written: $e^{-it}\left(p + \frac{dp}{dq}q\right) = \lambda$ (5) (λ is a constant)

The contrast with the conditions of competition is seen in the term $\frac{dp}{dq}$.

Since p corresponds to the net price, the expression (5) means that it is the discounted marginal profit which must be equalized over time $e^{-it}\Pi = \lambda$, either $\Pi = \lambda e^{it}$. Therefore, it is the marginal benefit of the natural resource (to be related to the marginal revenue) and not the price that must increase according to the interest rate.

$$\log \Pi = \log \lambda + \log e$$

$$\frac{dlog\,\Pi}{dt} = \Pi = i$$

The price will decrease more or less rapidly depending on the relationship between price and marginal income. Hotelling puts forward 2 reasons[4] for believing that the price will rise less rapidly and that the depletion of the mine will be delayed in a monopolistic market structure:

- The demand will be such that the resource will be exhausted in a finite time for a company subject to competition, and in an "infinite" time for the company with a monopoly. In a competitive market situation and depletion of mine, the price tends to move towards a finite value when demand approaches 0 (so the demand curve intercepts the ordinate axis at a certain value). In a monopolistic situation, resource depletion means that marginal revenue tends to move towards a finite value when demand approaches zero. Hotelling suggests that it is very likely that the first condition is satisfied but not the second, given that "*this is simply part of the general tendency for production to be retarded under monopoly*"(1931, p. 152).
- The numerical example given by Hotelling suggests that the competitive company and the monopoly company exhaust the deposit in a finite time, however the monopoly takes longer. The monopoly's tendency would be to keep output below the optimum rate and extort excessive prices from consumers[5]. Devarajan and Fisher

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[4] Stewart (1979; 1980) validated Hotelling's results under the assumption of an increasing extraction cost.

[5] According to Kay and Mirrlees, (1975) the fact that for many resources, the price is greater than the marginal cost when stocks are large would be tantamount to saying that the present price is substantially lower than the optimal or competitive price and that the resources in question are over-economized (meaning clear?).

(1981) illustrated the time path followed by price and extraction (in perfect competition and monopoly) in the figure below.

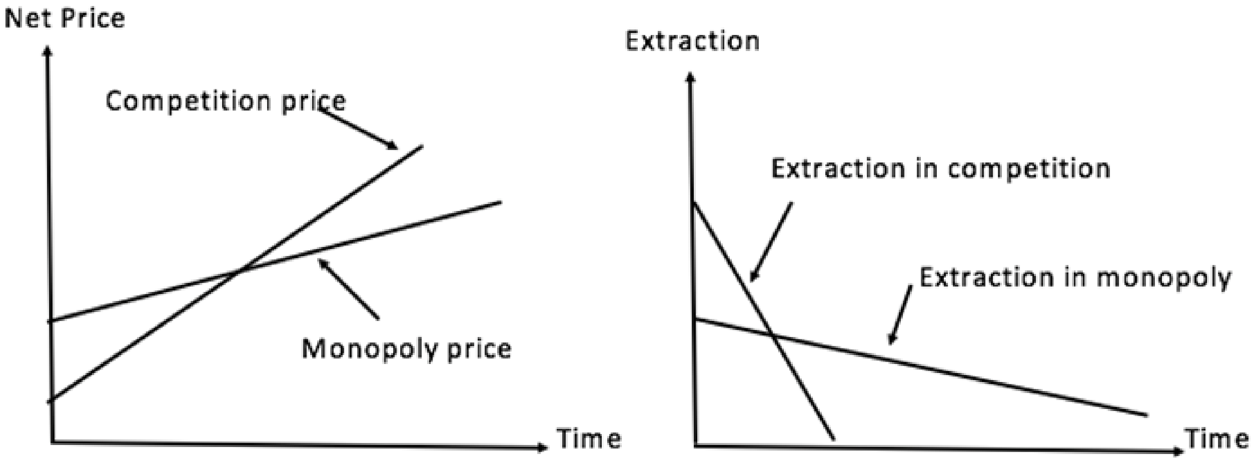

Figure-6. Extraction, Price and market's structure

Source: Devarajan and Fisher (1981)

Recalling that Hotelling's results are based on the characteristics of the demand function (linear and stable demand curve, decreasing elasticity when quantities increase), Devarajan and Fisher (1981) note that the reasoning is still valid when demand shifts over time by becoming more elastic (Stiglitz, 1976).

But let us return here to an important point of Hotelling's reasoning, the stocks are considered as given. This hypothesis illustrates the debates surrounding stock-flow dynamics and the position of economists. Adelman (1993) summed up this dilemma[6] in a few words: *"Minerals are inexhaustible and will never be depleted. A stream of investment creates additions to proven reserves, a very large in-ground inventory, constantly renewed as it is extracted. . .. How much was in the ground at the start and how much will be left at the end are unknown and irrelevant. (p. xi) The fixed stock does not exist. (p. xiii) What exists, and can be observed and measured, is not a stock but a flow"* (1993, p. xi, xiii, xiv).

This simplistic economic model of natural resource may be expressed in a CLD. The only stock is the stock of proven reserves, increased by a flow of investment and reduced by extraction.

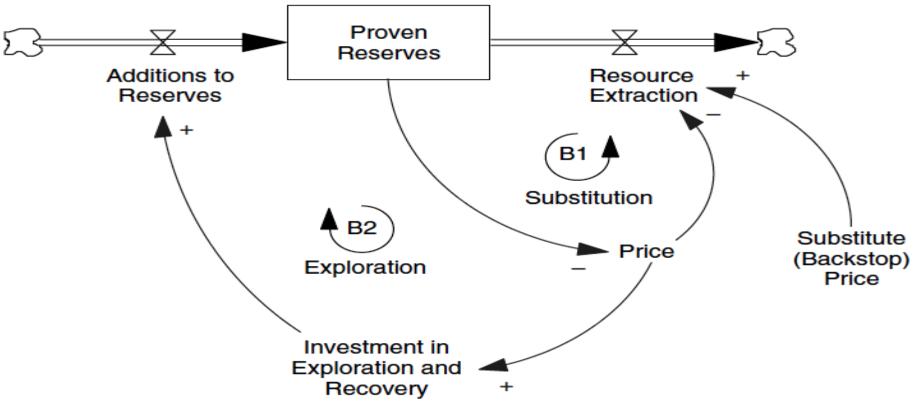

Figure-7. CLD of Stocks' Dynamics

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[6] For Sterman (2002) *"Adelman's statements violate conservation of matter. Every ton of titanium and every barrel of oil added to the stock of proven reserves reduces the stock of titanium and oil remaining to be found in the future. Every ton and barrel extracted reduces the quantity remaining in the ground. As exploration adds to the stock of proven reserves, the stock of undiscovered resource falls. Ceteris Paribus, the smaller the stock of resources remaining to be discovered, the lower the productivity of exploration activity must be, and the smaller the rate of addition to proven reserves will be for any investment rate. In the limit, If the stock of undiscovered resource fell to zero, the rate of additions to proven reserves would necessarily fall to zero*".

4. CASE STUDIES: PHOSPHOROUS AND INDIUM

In System Dynamics, a common practice is to define a reasonable system boundary, and analysis is then conducted within that boundary. We have used this method for two case studies: phosphorus and indium. We chose these two critical raw material for three reasons: (1) they are associated with two important sectors (phosphorus - fertilizers for agriculture and food industries; indium - metal industries (zinc), electronic industries and renewable energy; (2) the main producer is China (68% for phosphorous, 57% for indium, 44% for phosphate rocks), so the world economy is dependent on one country; (3) their end-of life recycling input rate is close to 0 (17% for phosphate rock) which is a big challenge for the circular economy in the future.

Table-5. Challenges for Indium, Phosphate Rocks and Phosphorous

	Main Global Producers (average 2010 – 2014)	**Main Importers to the EU (average 2010-2014)**	**Sources of EU supply (average 2010-2014)**	**Import reliance rate[7]**	**Substitution indexes EI/SR[8]**	**End-of-life recycling input rate[9]**
Indium	China 57% South Korea 15% Japan 10%	China 41% Kazakhstan 19% South Korea 11% Hong Kong 8%	China 28% Belgium 19% Kazakhstan 13% France 11% South Korea 8% Hong Kong 6%	0%	0.94/0.97	0%
Phosphate Rock	China 44% Morocco 13% United State 13%	Morocco 31% Russia 18% Syria 12% Algeria 12%	Morocco 28% Russia 16% Syria 11% Algeria 10% EU/Finland 12%	88%	1.0/1.0	17%
Phosphorous	China 58% Vietnam 19% Kazakhstan 13% United States 11%	Kazakhstan 77% China 14% Vietnam 8%	Kazakhstan 77% China 14% Vietnam 8%	100%	0.91/0.91	0%

Source: EC (2017)

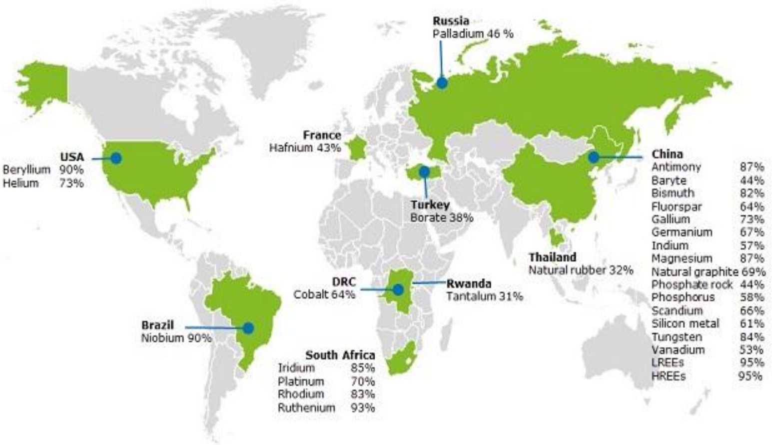

Figure-8. Countries accounting for largest share of global supply of CRMs

Source: EC (2017)

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[7] The import reliance rate takes into account global supply and actual EU sourcing in the calculations of supply risk. It is calculated as follows: EU net imports / (EU net imports + EU domestic production)

[8] The substitution index is a measure of the difficulty in substituting the material, scored and weighted across all applications, calculated separately for both Economic Importance and Supply Risks parameters. Values are between 0 and 1, with 1 being the least substitutable.

[9] The End-of-Life recycling input rate measures the ratio of recycling from old scrap to EU demand of a given raw material, the latter equal to primary and secondary material supply inputs to the EU.

4.1. Phosphorus Case Study

Alongside nitrogen (N) and potassium (K), phosphorus (P) is one of the three essential macronutrients needed for plant growth. In agriculture, more than 85% of the phosphorus-based fertilizer comes from mined phosphate rock (PR) (Cordell *et al*., 2009). Phosphorus is processed from the mineral apatite ($Ca_{10}(PO_4)_6(OH, F, Cl)_2$), mined from a very limited number of countries, notably Morocco, China, and the US. An extensive literature has been written on the limited availability of phosphorus, and there are widespread concerns that phosphorus production will soon peak or has already peaked (Dery and Anderson, 2007; Cordell *et al*., 2009). There are also concerns that the world´s nations will become increasingly reliant on Morocco´s vast phosphate rock reserves for imports, as this country consolidates its global position as the main exporter (Cooper *et al*., 2011). Those concerns were exacerbated in 2007-2008 when phosphorus prices increased more than 5 times to almost USD 500/ton, although the market has since stabilized at USD 120-140/ton (US Geological Survey, 2009).

Phosphorus is produced through the processing of phosphate rock, which is mined from a very limited number of countries. According to USGS latest estimations, Morocco and Western Sahara hold 75% of the world reserves (USGS, 2017). On the other hand, European countries have little or no phosphate rock reserves, a factor that has made Europe highly dependent on phosphorus imports. There are valid concerns with regards to the dependency of European agriculture on a handful of leading phosphorus exporters, and the five-fold increase in phosphorus prices in 2007-2008 showed how unpredictable and volatile the market can be, with adverse effects on the European food production sector and the food security of European citizens. Import dependency and market volatility convinced European policy makers to include phosphorus on the list of critical raw materials.

Phosphate rock is mainly extracted by open-cast mining, which involves a range of processes with a direct impact on the landscape and the environment, such as the removal of topsoil and overburden. Phosphate mining generates millions of tons of waste, and phosphate processing creates a large volume of sludge, the rock waste and sludge are deposited in rock piles and ponds in the vicinity of the mining area (Hakkou *et al*., 2016). It also leads to rock desertification, an aesthetic depreciation of the landscape, and increases the risk of landslides and ground erosion (Yang *et al*., 2014). Normally, countries require mining companies to carry out reclamation of land after the mines are exhausted – this includes contouring (returning the site to the pre-mining geomorphology) and re-vegetation. However, many of the more than 200 closed mines in Morocco have had no post-closure management plan, which effectively means that the waste generated by mining is still *in situ* and no reclamation activities have been carried out (International Development Research Center, 2014).

There are lessons to be learnt from other countries in the world where phosphate rock mining was equally important for the national economy. In the Republic of Nauru, for instance, the environment was critically damaged by open-cast mining for phosphate rock. Biodiversity-rich habitats were scraped off in the search for the phosphate ore, and with no post-mining restoration strategies, the formerly mined land was made inhospitable for most life forms. Moreover, the newly formed wasteland also contributed to more frequent droughts (Fraser and Nguyen, 2005) which may also be of concern in Morocco and Western Sahara due to their low rainfall rate climatic characteristics. Managing land resources sustainably is also important for Morocco in the context of national food security for a growing population. From 1960 to 2015, Morocco´s population grew from 11 million to 34 million and is expected to reach 42 million by 2050 (WB, 2015). This will inevitably require more land for agricultural production in order to secure food supply, agricultural land which is itself also in competition with the build-up of infrastructure and the expansion of urban areas.

Water security is another issue to be considered, because the storing of highly hazardous by-product waste phosphor-gypsum can lead to serious leakages and pollution of groundwater. In the US´s largest phosphate mining site in Florida, a sinkhole opened underneath a gypsum stack in 2016, leading to more than 215 million gallons of contaminated water entering the Floridan Acquifer, which supplies water to 60% of the people in Florida (Sierra Club Foundation, 2016). In addition to water pollution, large amounts of water are used in the processing of phosphate rock, and although the OCP claims that 95% of the wastewater is reused, the remaining 5% is still a significant amount of water that is diverted from human consumption. The World Resource Institute has already shown that by 2040, Morocco will be one of the world´s most water-scarce countries, with a water-scarcity score of 4.68 out of 5 (WRI, 2015).

Mining of phosphate rock is closely linked to the food production system, which in turn is influenced by consumption patterns in society, the type of farming systems, global market economics, and the approach of governments and societies to environmental pollution.

The Causal Loop Diagram for phosphorous depicts the cross-sectoral interactions between society, government, and management of natural resources in the case of phosphorous.

Social aspects are included in the diagram, Figure 9, shown in a violet color, in order to demonstrate the application of the System Dynamics methodology, in which the biophysical and economic aspects, shown in blue color, are combined with social ones. 2 loops are included in the diagram to show the interconnectedness between the biophysical elements of phosphate rock, the market dynamics, and the social aspects involved. We start with a driving reinforcing loop (R1) and envision a business-as-usual scenario, where an increase in food production leads to an increased need for nutrients on farms and consequently to more phosphate rock (PR) mining for phosphate fertilizer production. Having P as a readily available source will in turn further incentivize food production. However, both food production and PR mining and processing lead to increased environmental pollution and degradation. From here, there are 2 reinforcing loops and 4 balancing loops that drive the system. The balancing loops B1, B2 and B3 represent the connections between the biophysical and the economic aspects. The more P is mined, the higher the stocks of P become, lowering the price of phosphate rock on the market. A lower price can lead to less investments in the field, thus reducing the productive capacity of the sector, resulting in decreased mining for phosphate rock, decreasing P stocks, and affecting the price. Recycling can help to maintain the stocks. As the price responds to the available stocks on the market, so does demand, resulting in a change in the ratio between the supply and demand of the resource, which in the end causes changes in the price.

The loops labelled R2 and B4 show that the costs for environmental rehabilitation and the increased healthcare costs resulting from environmental degradation have a negative impact on the state budget. With less money to spend in the state budget, government activity will be jeopardized and thus the quality of public service will decrease. However, when the environmental regulations are enforced, it has a positive effect, resulting in less environmental degradation and pollution.

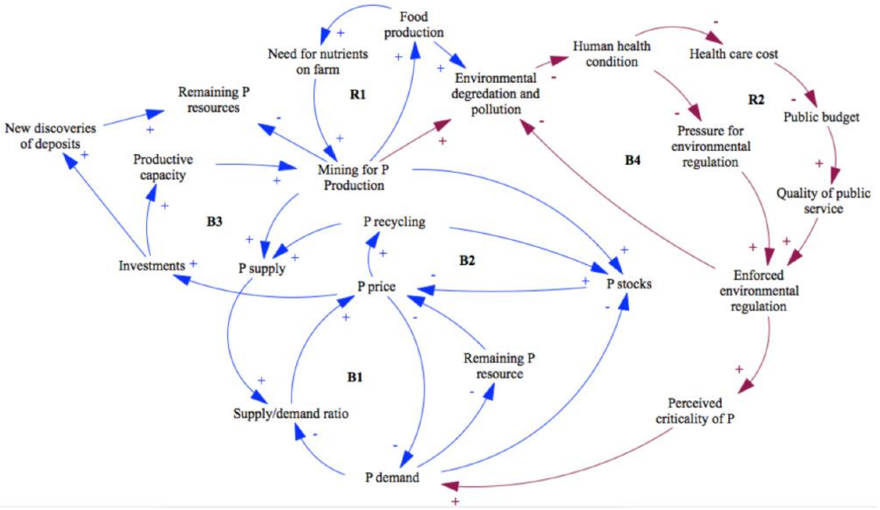

Figure-9. A causal loop diagram representing the dynamics of phosphate rock mining

It can also be argued that when environmental regulations are introduced and enforced, it can result in an increased level of perceived criticality of the resource, which could increase the demand for it. This may be due to the fact that it often takes time for industries to respond to new rules and regulations, causing delays in the system. At least there will be the expectation that it will take time for the industry to adjust, thus increasing the perception that supply disruptions could occur.

As a response to the challenges and problems that emerge from the system, governments can opt to support more sustainable farming practices and thus decrease the need for nutrients on farms; support P recycling at a national level and thus decrease the need for PR mining (R9); and/or support a more sustainable P production and supply chain.

4.2. Indium Study Case

To present the indium system, the boundary must be established within which the system interactions that give the system its characteristic behavior take place. Because indium is a by-product of zinc mining and refining, demand and supply of zinc have to be included. Zinc demand is mainly influenced by the economic growth of various sectors. Zinc's effectiveness in protecting steel against corrosion by galvanizing is well recognized, while its ability to die-cast complicated components makes zinc indispensable in a multitude of industry and household products. It also has important markets in the brass and construction industries and in chemicals and constitutes an essential nutritional element.

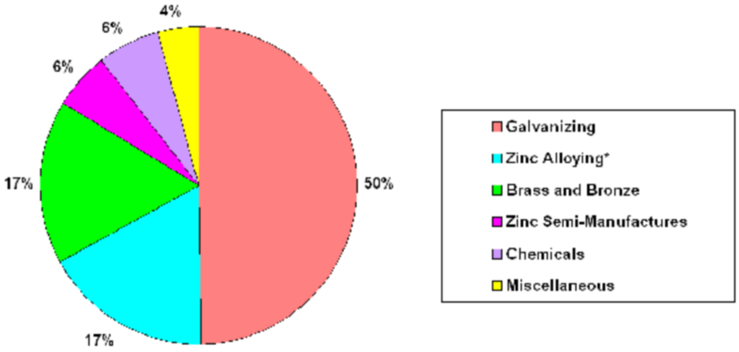

Figure-10. End Uses of Zinc

Source: International Lead and Zinc Study Group (2018)

Zinc supply relies on primary production (mining) and secondary production (recycling from end of life products).

Table-6. World refined Zinc Supply and Usage 2012 – 2017 (000 tons)

	2012	2013	2014	2015	2016	2017 (Aug)	2017 (Sept)	2017 (Oct)	2017 (Nov)
Mine Prod	12,896	13,039	13,493	13,610	12,769	1,081.1	1,142	1,228.8	1,232.4
Metal Prod	12,595	12,979	13,478	13,656	13,724	1,112.8	1,165.7	1,212.4	1,233.9
Metal Usage	12,380	13,148	13,754	13,486	13,861	1,154.3	1,200	1,253.6	1,314

Source: ILZSG (2018)

Indium is most commonly recovered from the zinc sulfide ore mineral sphalerite. The indium content of zinc deposits from which it is recovered ranges from less than 1 part per million to 100 parts per million. Production of indium tin oxide (ITO) accounts for 80% of global indium consumption (Choi *et al.*, 2016). ITO thin-film coatings are primarily used for electrical conductive purposes in a variety of flat panel displays, most commonly liquid crystal displays (LCDs). Other indium end uses included alloys and solders, compounds, electrical components and semiconductors. Indium is most commonly recovered from ITO scrap in Japan and Republic of Korea.

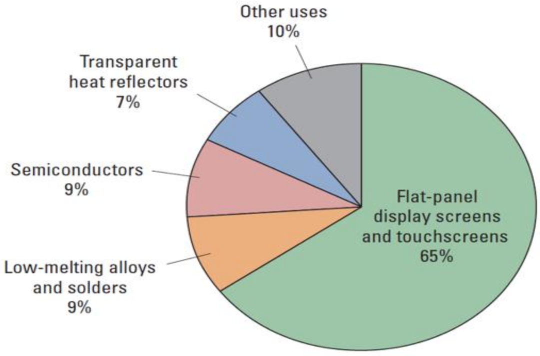

Figure-11. Major end uses of Indium
Source: USGS (2017)

Data on the quantity of secondary indium recovered from scrap are not available and the last research (Wellmer and Hagelüken, 2015) estimated at 1% the recycling rate of indium. It seems that the challenge is there. Sverdrup and Ragnarsdottir (2014) considered that 50% of indium recycling would extend the life of supply by 38 years (190 years for 70% recycling).

Table-7. World Refinery Production (tons)?

	2015	2016	2017
Belgium	20	20	20
Canada	70	71	70
China	350	300	310
France	41	-	20
Japan	70	70	70
Korea (Republic of)	195	210	215
Peru	9	10	10
Russia	4	5	5
United States	-	-	-
WORLD TOTAL	759	680	720

Source: USGS (2018)

For the United States, indium is a strategic resource (120 tons imported for consumption in 2017 and no government stockpiling), and import sources may be a problem for security. From 2012 to 2015, the United States imported indium from Canada (25%), China (14%), France (13%), Belgium (12%) and others (36%). When France stopped producing indium in 2016, United States became more dependent on China (22%). So, the world indium consumption and the price market are linked to Chinese production and export policy. In November 2016 and 2017, Fanya Metal exchange warehouses reportedly held 3,600 tons of indium (and no information was available as to when the inventory would be released into the market). In 2017, China's Ministry of Commerce implemented an export license system and eliminated the previous used quota system which limited the amount of indium that could be exported. This new policy is expected to encourage exports of indium (USGS, 2018) and to increase the market price (322 dollars per kilogram on February 26, 2018).

Figure-12. Price of indium, dollars per kilogram

Source: Les Echos, February 26, 2017

Table-8. Price of indium, annual average, dollars per kilogram

	2012	2013	2014	2015	2016	2017
New York Dealer	540	570	705	520	345	360
Free Market	NA	NA	NA	410	240	205

Source: USGS (2018)

According to the American Indium Corporation, indium tin oxide (ITO) demand will keep growing in 2018 (5.5% annual rate) to reach 1,680 tons in 2019 (in 2016, the demand was 1,356 tons). This increase (+ 25%) will mostly come from China (50% in 2019 against 40% in 2016) and South Korea.

The Causal Loop Diagram for indium depicts the cross-sectoral interactions between an economic pillar (business model), an ecological pillar (environmental regulation), and a social pillar (society and human health). Indium is a by-product of zinc mining and refining, so demand and supply of zinc have to be included.

From the business perspective, indium supply is exclusively from primarily production and recycling processes. Indium production may lead to an accumulation of indium stock but decrease indium reserves. There is a reverse relation between indium demand (ITO, LED, Solar Electric) and stocks (and reserves). An increase in demand reduces stocks and reserves of indium. The reinforcing loop R1 (growth of demand increases the price of indium) interferes with a balancing loop (B4), where an increase in the price of indium leads the industries to find substitutes and to reduce indium demand. From the environmental and social perspective, the more indium production there is, the more environmental degradation and pollution can occur. With increased pollution comes worse human health conditions, resulting in increased pressure for environmental regulation to protect both humans and the environment. This pressure results in increased enforcement of environmental regulations, which ultimately results in reductions in the environmental degradation and pollution. The process described can be seen in loop B6, representing a balancing effect or counteractive behavior. A reinforcing loop that could easily interfere with the balancing loop we just described can be seen labelled R2 in the diagram. With worse human health condition of the public due to pollution, the cost of health care would increase, affecting the government budget negatively. As the budget decreases, the quality of the public service goes down since financial resources are essential for its effectiveness. Among other things, the government would have less capabilities to ensure enforcement of environmental regulations, given that the quality of public service had decreased. When environmental regulations are not enforced, the result would be increased environmental degradation and pollution. Increased enforcement of environmental regulations could also cause higher levels of perceived criticality of indium, as discussed above for phosphorus.

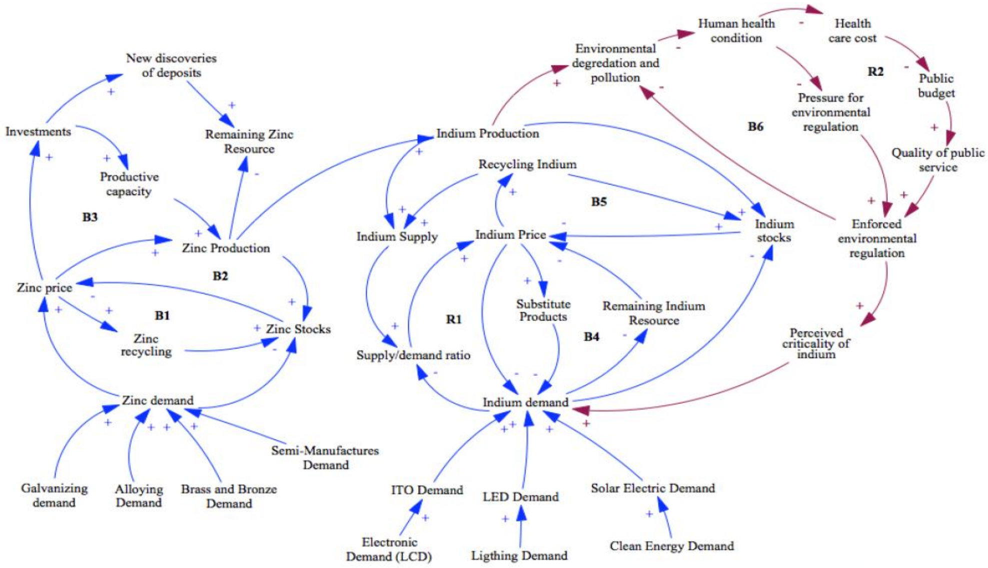

Figure-15. CLD for indium

When examining the policies for Critical Raw Materials (CRM) in the developed world, as seen in reports from the EU, Japan, China and the USA, it becomes apparent that they are ultimately aimed at securing the supply of these materials for their industries and economic activities. The assumption that ensuring national or regional economic interests will provide social well-being, seems to be implicit. However, publishing such lists does not happen in a vacuum, and the CRM lists could give signals which trigger processes leading to worsening social conditions, especially for the developing countries producing the CRMs. Increased perceived criticality of materials could lead to increased demand for them, resulting in more pressure on mining communities to produce more materials since the price is expected to go up. This increased pressure could have unwanted consequences, such as increased environmental degradation and pollution, human rights violations, illicit trade, poor working conditions, and resource conflicts. Governments in the developed world must acknowledge that there are limits to the Critical Raw Material lists, because they often ignore the social aspects of criticality and the social context in which materials begin to be perceived as critical.

5. CONCLUSIONS AND RECOMMENDATIONS FOR SUSTAINABLE POLICIES

Raw materials are considered crucial to the world economy. They are essential for maintaining our welfare, they underpin the functioning of our industry, and make possible modern technologies, such as green energy production and communications. Supply shortages of these materials, or market price spikes in crisis years, triggered the development of criticality assessments for raw materials by government agencies. We present the commonly-used methodologies for criticality assessments from the USA, Japan, the EU and the World Bank. We show that existing methodologies are compound indicators, represented within a criticality matrix, based on economic indicators of supply risk and economic importance. In the EU, work on criticality assessments has advanced in recent years with recommendations to include a number of other factors in the methodology. These factors are related to i) land use competition: ii) mining governance; iii) by-product dynamics; iv) supply chain; and v) environmental and social considerations. Nonetheless, we argue that current methodologies still identify critical raw materials from a macro-economic perspective, and do not tackle issues related to sustainable development. Paradoxically criticality assessments have the potential to increase raw material criticality. This can occur either by a market signal that results in increased prices for raw materials, or by increased conflict over critical materials.

To tackle these methodological shortcomings, we propose a complementary methodology stemming from System Dynamics Modelling. By presenting 2 case studies for Phosphorus and Indium, we demonstrate the value of this proposed method which provides more information and guidance for policy development. Our method helps in clarifying underlying causalities and identifying driving forces and leverage points in the dynamics of criticality. We argue that our method allows policy- and decision-makers to take social and environmental aspects of critical raw materials into account. A key leverage point for policy-making is accountability for environmental degradation and pollution, which requires policy-makers to consider a shadow price for raw materials which includes externalities. From this perspective, reduced criticality can be achieved by enforcing stricter environmental regulations and boosting the recycling sector with the double purpose of improving supply security and ensuring environmental and human health. These analyses addressed the global market, as well as social and environmental situations common to other raw materials. We suggest that our method is transferable to other raw materials (e.g. Tantalum in Democratic Republic of Congo[10]), as long as any variables particular to the analyzed material are accounted for. We encourage the use of System Dynamics Modelling to assess the drivers of criticality for these and other raw materials, and to provide valuable insights for policy-makers about how to reduce criticality, and how to work towards a raw materials supply that takes into account not only economic but also environmental and social issues.

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[10] We plan to study the case of tantalum because this critical raw material is covered by the *Conflict Minerals Regulation* (Regulation EU 2017/821) establishing an Union system for supply chain diligence to curtail opportunities for armed groups and security forces to trade in tantalum. If Rwanda (31%) and Democratic Republic of Congo (19%) are the main producers of that CRM, main source of EU supply is Nigeria (81%).

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