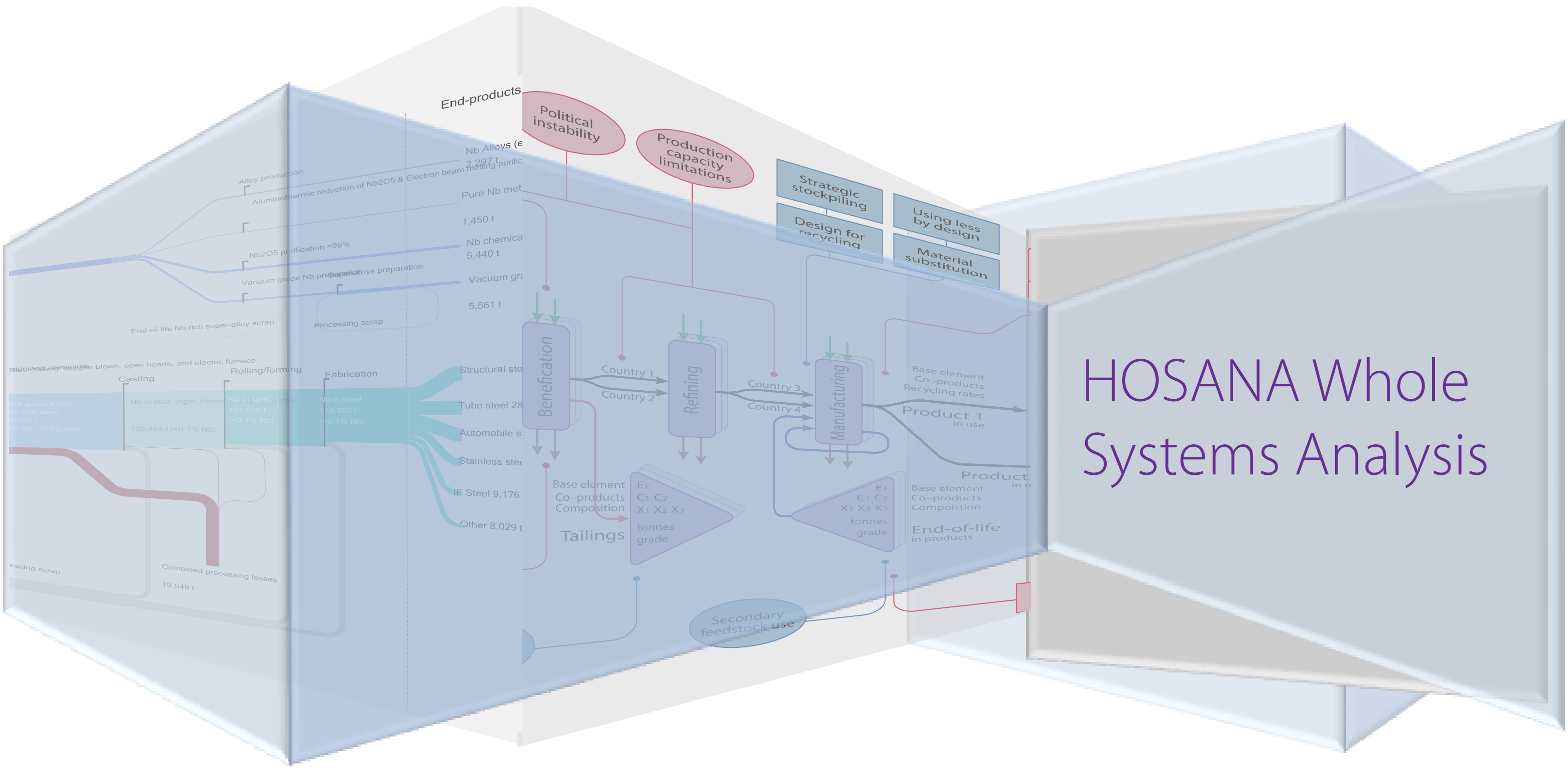
$$\text{Mineral Criticality} = \frac{\text{Capacity Risk}}{\text{Capacity Readiness}}$$

Devising swift responses to critical mineral supply capacity risks and disruptions



Mineral Criticality = $\frac{\text{Capacity Risk}}{\text{Capacity Readiness}}$

Hosana Whole Systems Analysis

The HOSANA project has been designed as an 8-month scoping study funded by the UK government to explore options to mitigate supply risks associated with technology metals used in clean energy technologies and other digital products, starting with twelve elements selected by the UK's Natural Environment Research Council (NERC): Li, V, Co, Te, Se, Nd, In, Ga, HREE, C, Nb and PGMs. The aim of the scoping study is to identify knowledge gaps and potential technical, science, business, or policy innovations that would reduce the risk of short or long-term shortages for these elements.

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British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

NERC SCIENCE OF THE ENVIRONMENT

First published May 2014

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Executive Summary

The business risks of material criticality are not that the earth's reserves will be consumed, but are that the supply chain cannot respond rapidly enough to demand or supply shocks. Managing this risk depends on understanding the speed at which alternative supplies can be brought to market, and the risks can be reduced by increasing the readiness of new capacity throughout the supply chain.

These new insights are a step change from previous approaches to criticality which have focused on the supply of ore from existing mines and are the key findings of a preliminary whole systems analysis of material criticality:

- Capacity risks which arise when demand outstrips supply may occur due to monopolistic behaviour in the supply chain, political instability in producing countries, demand surges, competition from new or rival industries. When such risks lead to supply or demand disruption they create price volatility in mineral commodities markets, and in extreme cases lead to supply shortage.

- When this occurs, actors throughout the supply chain will attempt to restore the balance in the system according to their capacity readiness for example by expanding mine production, increasing input from secondary feedstock, using materials more efficiently, or switching to substitutes.

- Mineral criticality can therefore be mitigated by increasing the readiness of alternative capacity, for example through better understanding of alternative mineral deposits including existing tailings, improved processing with higher yields throughout the supply chain, or better planning for recovery and recycling from in-use stocks.

In our preliminary analysis, we mapped the global supply chains of four critical elements from mine to product, and sent our results to key experts around the world, whose interests spanned mining, trading, distributing, processing, manufacturing, recycling and regulation. We then conducted an "expert panel week" with twenty nine hour-long interviews with these experts, to critique our analysis, and probe our understanding of mineral criticality, which is summarised in this report. Having understood this new definition of mineral criticality, we can now recognise three key knowledge gaps that inhibit our ability to reduce risks to businesses and governments throughout the mineral supply chain. In parallel with this report, the second outcome of our preliminary project is a proposal for a full-scale research project to develop a practical business and policy support tool to assess the risks of mineral criticality, and to increase capacity readiness through improved knowledge of geological and processing options. The three key knowledge gaps are:

Towards a Capacity Risk and Readiness Evaluation Tool

In our preliminary analysis, we characterised the global supply chain of four representative elements (In, Nb, PGMs and Co) [Pages 2-3] by mapping their material flows across the production system, from mining to final application and disposal. Five general observations emerged from this analysis: (1) there is no long-term geological scarcity of these elements, but they are unevenly distributed in the Earth's crust, leading to production concentration by a few mines and countries; (2) overall, large material losses exist around these supply chains (78%, 44%, 26% and 77% for indium, niobium, platinum group metals and cobalt respectively); (3) material losses mostly occur during the upstream beneficiation and refining stages; (4) input from end-of-life recycling is generally low compared to losses for these elements (<23%); and (5) our understanding of the supply chain of these elements is limited by data unavailability.

Discussion of our results with industry specialists during our "expert panel week" suggested that although our rough-cut supply chain characterisations are useful in their current state, they still do not address some of the knowledge gaps that inhibit stakeholders' responsiveness to capacity risks. As a result of this, we have defined a layout for a dynamic integrative supply chain analysis that goes beyond mass flows, to allow users to locate capacity risks over time and identify opportunities to improve capacity readiness and accelerate responses to future supply chain shocks [Pages 4-5].

Capacity Readiness Through Geological Understanding

Evidence gathered during the expert panel week indicates that some of the risks associated with critical metals resources can be mitigated through co-production of critical metals with other critical metals, or with other industrial and/or precious metals. In order to determine the critical metal deposits that might be most fit for resilient co-metal production, research is needed that elucidates: (1) The geological processes that produce variations in co-metal/mineralogical combinations, such that co-metal ore type domains can be incorporated into regional geological models, which in turn facilitate predictive models for exploration and more robust resource estimation; (2) Use of the mineral chemistry and mineral associations/relationships of co-metal ore types within deposits to examine deposit suitability for a more responsive supply and to develop a broader understanding of crustal stocks. This research area is described on Page 7 of this report.

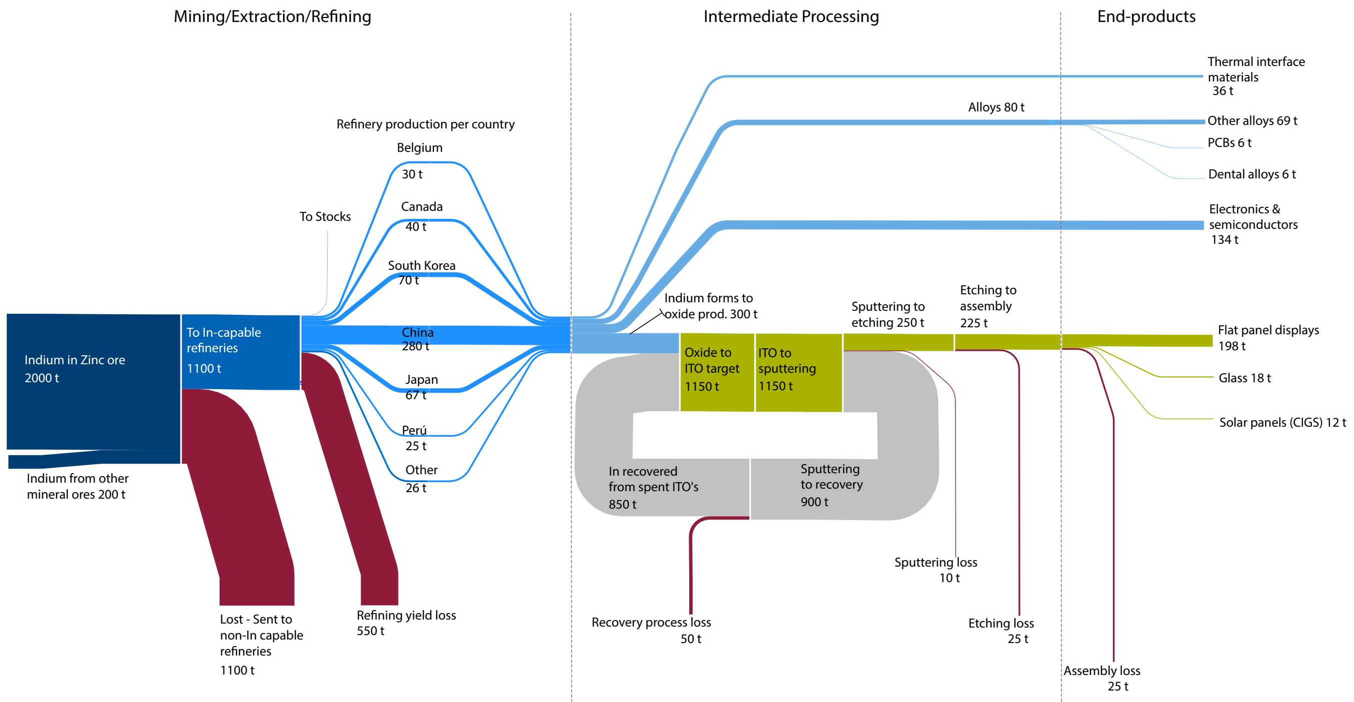
Capacity Readiness Through Better Mineral Processing

Our global mass-flow maps of In, Nb, PGMs and Co show that metal losses during beneficiation and refining are disproportionately high compared to losses from the rest of the lifecycle. In parallel with the need for better understanding of the geological formation and chemistry of mineral deposits, research is therefore required to develop geometallurgical models for mineral processing to examine disaggregation and liberation of ore mineral and identification of viable mineral processing routes. In addition, it is necessary to characterise the physical, technological and economic factors that govern ore processing methods. Research in this area, described on Page 8 of this report, is particularly required to: (1) allow rapid identification of geological deposits that can be exploited economically, leading to new mines or the addition of co-production of strategic minerals to existing operations; (2) to reduce the losses of strategic minerals from current mines. This will include engaging with the relevant stakeholders to understand the financial drivers, and the process and technological shortcomings from existing mining operations.

Rough-cut supply chain characterisation

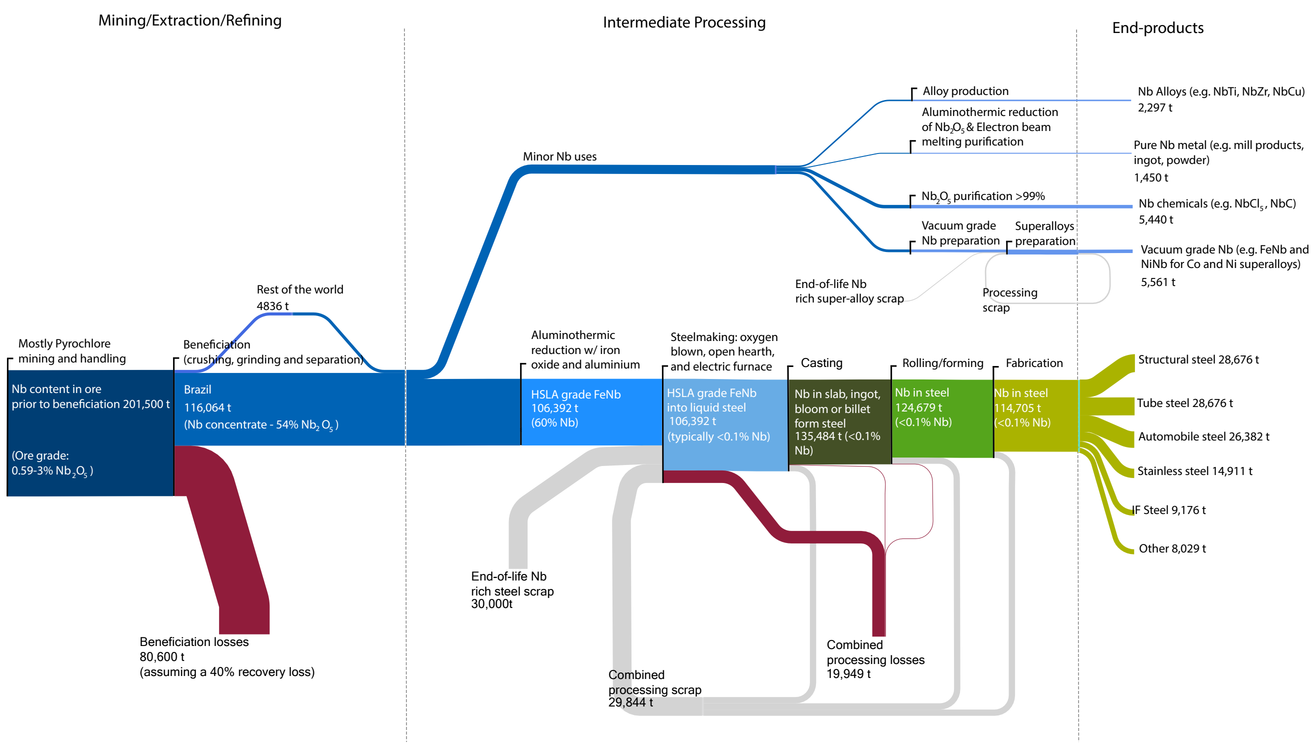
The Sankey diagrams in this section characterise the supply chain of four elements (In, Nb, PGMs and Co) to identify key bottlenecks and resource efficiency improvement opportunities by mapping their material flows, from mining to final application and disposal. The key messages obtained from each supply chain are summarised under each diagram.

Figure 1: Global Indium Mass Flow In 2009



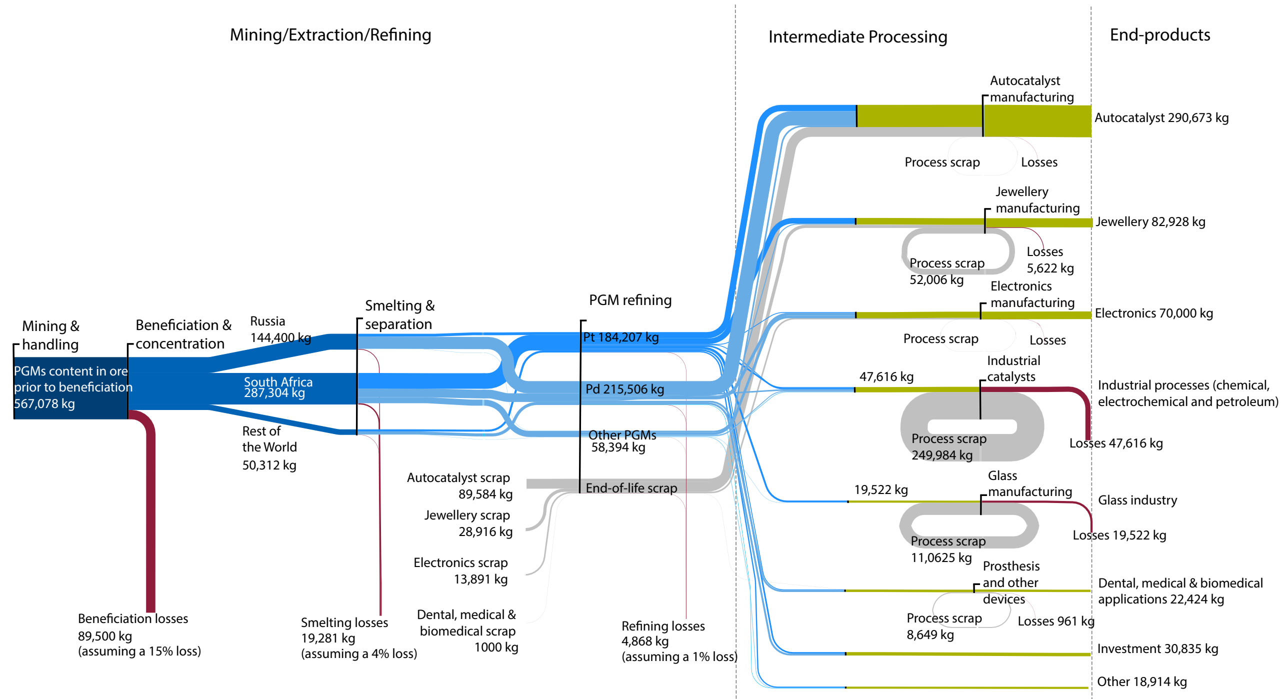
Key messages: i) all indium is mined as a by-product of base metals. Most indium is extracted from zinc processing residues; ii) nearly 50% of indium is lost due to zinc ores being processed in non-indium producing zinc refineries; iii) the average indium recovery rate in indium producing zinc refineries is around 50%; iv) recycling is almost non-existent.

Figure 2: Global Niobium Mass Flow In 2011



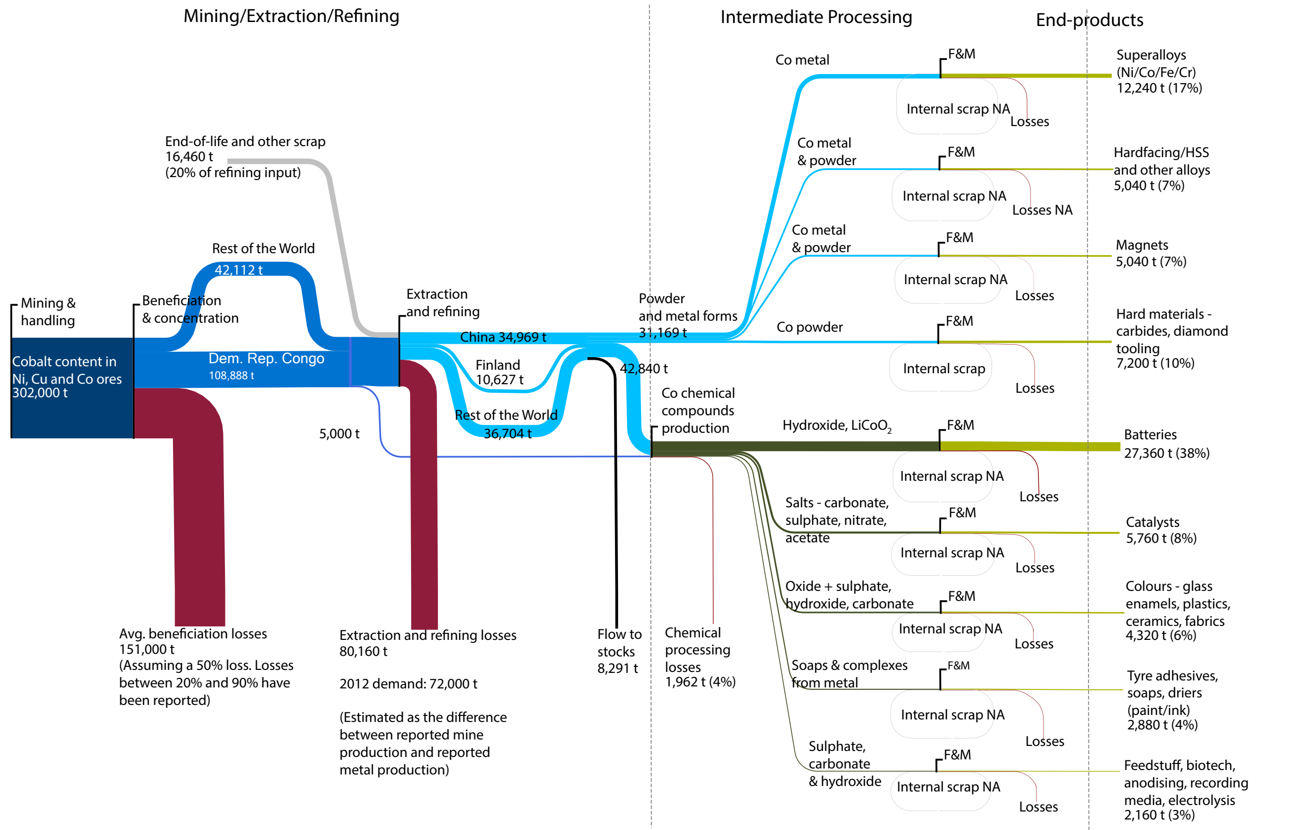
Key messages: i) most niobium is extracted as a primary ore from pyrochlore minerals; ii) the average beneficiation recovery rate is around 60%; iii) niobium mine production is dominated by Brazil (96%); iv) most niobium (88%) is converted to HSLA grade FeNb for steel production; v) once niobium is embedded in steel it is not usually recovered again as a single element and becomes diluted within the liquid steel pool.

Figure 3: Global Platinum Group Metals Mass Flow In 2010



Key messages: i) South African PGMs are mined as primary ores while Russian PGMs are mined as by-products of nickel-copper ores; ii) the largest material losses occur during the beneficiation and concentration stage (15%); iii) smelting and refining losses are comparatively lower (4% and 1% respectively); iv) end-of-life recycling accounted for approximately 23% of total input in 2010.

Figure 4: Global Cobalt Mass Flow In 2011



Key messages: i) cobalt is mostly mined as a co-product with copper and/or nickel; ii) beneficiation recovery rates between 20 and 90% have been reported (a 50% value is assumed in here); iii) the Democratic Republic of Congo concentrated 72% of global cobalt mine production in 2011; iv) a recovery rate of 52% was allocated to the extraction and refining stage; v) end-of-life scrap represents only 20% of the input material for the refining stage.

Towards a capacity risk and readiness evaluation tool

Our maps of In, Nb, PGMs and Co (previous page) display the allocation of these materials across their supply chains by following the mining and processing-manufacturing-use route for each element, the recycling and re-use flows, and the points where material losses occur. These maps highlight the total amount of materials that were extracted, processed and used during one specific year, but do not indicate the accumulated natural and anthropogenic material stocks available for human exploitation. This methodology has proved to be a useful way to identify key bottlenecks, resource efficiency improvement opportunities, and knowledge gaps in the supply chain. However, evidence gathered during our "expert panel week" suggests that supplementary information could be added to increase the knowledge base and transparency of mineral supply chains, including:

- Natural stocks in Earth's crust and their composition
- Anthropogenic stocks and their composition
- Resource intensities (e.g. water, energy, and so on).
- Emissions to the environment (e.g. mine waste, CO_2 emissions, leachate, and so on).
- Element linkages along the chain (i.e. map of all other elements that accompany a specific compound material through its life).
- Recycling rates and recyclability indicators.
- Price volatility.
- Geopolitical risks of production concentration.
- Information about toxicity risks and legislation.

We have defined a new layout for an integrative supply chain analysis that goes beyond mass flows (below) and incorporates the supplementary information listed opposite. The aim is that by increasing the knowledge base about specific material supply chains, it would be easier for stakeholders to locate supply capacity risks and visualise strategic capacity readiness areas where intervention is most required to maximise impact and facilitate criticality responses, effectively improving the time required to re-balance the system. The integrative layout (below) represents a static snapshot of material flows during one specific year and this characteristic limits its ability to anticipate future supply-demand imbalances, as these are dynamic phenomena. Consequently, it is necessary to convert this layout into a dynamic tool that allows stakeholders to visualise the influence of several key variables on the supply chain, including the effect of future demand scenarios on material requirements, resource intensities, and environmental impacts associated to greater material extraction and processing. The creation of this tool would require four development steps:

1. Comprehensive Supply Chain Characterisation

The fundamental requirement in this process is to generate mass flow analyses for all strategic metals identified by the UK's Natural Environment Research Council (i.e. Li, V, Co, Te, Se, Nd, In, Ga, HREE, C, Nb and PGMs), and for any other elements of interest for the project stakeholders, of the form of the analyses that we have already performed for four elements, to use them as a solid base from which to start developing more detailed and complex supply chain models.

2. Sustainability Indicators

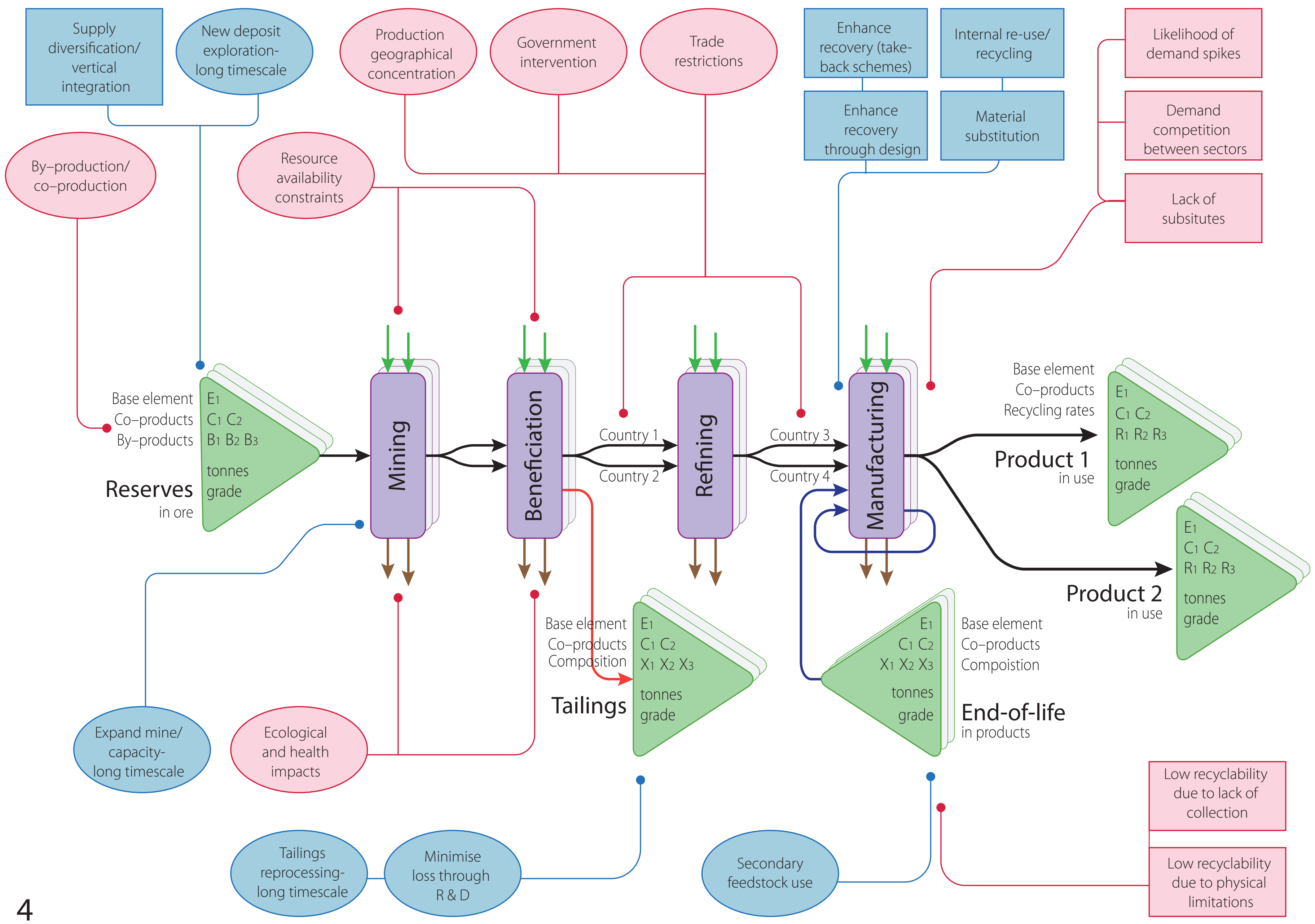
Sustainability indicators such as energy, water and chemicals consumption, as well as carbon dioxide emissions, are usually not published by technology metals mining and refining companies. Therefore the true environmental effects of their operations are unknown. The research challenge is clear: it is necessary to engage with the stakeholders that hold such information in order to cover the enormous knowledge gaps that exist in this area and provide detailed insight into the processing technologies, resource intensities and environmental emissions associated to critical metals extraction and processing, and how these variables could affect future demand and supply.

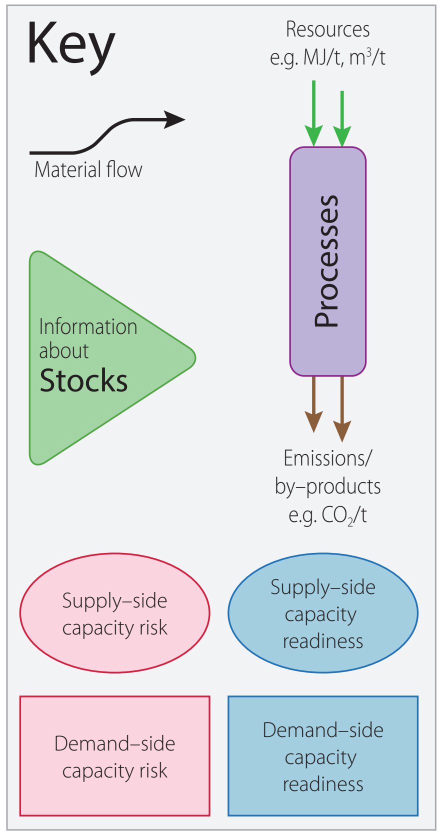
3. Characterisation Of Interconnected Metal Cycles

Metals do not exist in isolation in nature and are usually combined with other elements in minerals. Recovering single elements from these interconnected mineral structures is an extremely energy intensive and complex procedure. Once elements are isolated and refined, the production system combines them again to form a wide range of human-made compounds that are chemically and physically dissimilar to the natural mineral structures where these elements were originally extracted from. In order to achieve a whole systems view of material criticality, it is necessary to understand how demand for one element influences other metal cycles, including the resource stresses and environmental impacts that they exert on those interlinked metal systems.

4. Integration Of New Dynamic Supply Chain Tool

The inputs to the dynamic tool will include forecasts of mineral elements demand as well as editable processing technology scenarios to predict how technology performance and selection (e.g. between bio-processing or leaching) may affect the capacity of supply to keep up with demand, and how sustainability indicators (resource intensity and environmental impacts) along the supply chain may evolve over time. Editable scenarios will also include the range of traditional responses usually undertaken to deal with supply-demand imbalances, both in upstream and downstream processes (e.g. starting new mines, stockpiling, etc.). The tool will allow sensitivity studies to predict the value of technology innovations and the impacts of increased material consumption on interconnected metal cycles, including potential supply-demand imbalances that could lead to temporary scarcity or price volatility.





The supply chain layout shown here measures material flows across the production system and time, employing this knowledge as a starting point to track material stocks, quantify capacity risks, and evaluate the overall capacity readiness of the system. By doing this, the layout allows the identification of key areas where intervention could lead to increased capacity readiness and faster supply-demand re-balancing within the system. Further information about the capacity risks and capacity readiness categories shown here can be found on the next page.

Capacity risks and capacity readiness explained

Evidence gathered during the expert panel week suggests that the business threats of material criticality are associated to the speed at which the supply chain can respond to demand or supply shocks. Managing these threats depends on understanding the sources of capacity risks affecting supply and demand, the likelihood of capacity risks developing into disruption events, and the possibilities for increasing the readiness of new capacity throughout the supply chain. Numerous capacity risks exist on both the supply and demand sides, including (non-exhaustive list):

Supply	Demand
▪ Reserves concentration (lack of natural deposits diversity). ▪ Production geographical concentration. ▪ Political instability in producing countries. ▪ Government interference due to national security/strategy. ▪ Commercial reliance on a single commodity (lack of output diversity due to by- and co-production). ▪ Physical availability in earth's crust. ▪ Resource availability and costs (e.g. water or energy). ▪ Social and legislation constraints due to ecological and health impacts.	▪ Likelihood of demand spikes due to new technologies or markets. ▪ Demand competition between industries, technologies or sectors. ▪ Lack of substitutes. ▪ Low recyclability due to physical segregation limitations. ▪ Low recyclability due to lack of end-of-life collection.

Table 1 - Capacity Risks

Capacity risks do not always transform into disruption events, but when they do, these events can occur on both the supply and demand sides, expressed in different ways, including (non-exhaustive list):

Supply (production disruption)	Demand (change in patterns)
▪ Labour disputes. ▪ Resource constraints (e.g. water or energy). ▪ Natural disasters. ▪ Problems/absence of transport infrastructure. ▪ Geopolitics leading to government intervention, resource nationalisation and/or trade restrictions (e.g. export quotas). ▪ Legislation restrictions due to ecological and human health concerns (e.g. REACH). ▪ Social unrest/armed conflicts.	▪ New disruptive technologies increasing demand and competition for materials. ▪ Substitution of an element in one technology leads to increased demand for other elements. ▪ Legislation restrictions (e.g. REACH). ▪ New markets (e.g. China, India) leading to increased demand.

Table 2 - Disruption Events

Capacity risks and disruption events combined lead to supply-demand imbalances, usually manifested as price volatility in the mineral commodities markets. When this occurs, the different stakeholders along the chain react according to their own interests and capabilities (capacity readiness). Traditional responses to supply-demand imbalances include (non-exhaustive list):

Supply	Demand
▪ Expand capacity in existing mines (long timescale, subject to physical and economic feasibility). ▪ New mineral deposits exploration and exploitation (long timescale, subject to economic certainty). ▪ Commence or expand by-product and co-product output (short timescale). ▪ Process old mine waste/tailings (long timescale, subject to technical and economic feasibility). ▪ Optimise/minimise production losses through R&D investments (long timescale) ▪ Increase input from secondary streams (short timescale, subject to physical and technical availability).	▪ Support entrance of new suppliers in the market (long timescale). ▪ Internal manufacturing reuse/recycling (short timescale, subject to technical and economic feasibility). ▪ Enhance end-of-life recovery through take-back schemes (long-term, subject to economic and logistical feasibility). ▪ Enhance end-of-life recovery through more accessible design (long-term, subject to technical feasibility). ▪ Material substitution (short timescale, subject to substitution potential). ▪ Minimise manufacturing losses through R&D investment (long timescale, subject to technical feasibility). ▪ Vertical integration (short timescale). ▪ Buy from other industries that can substitute.

Table 3 - Capacity Readiness

The responses that form part of our capacity readiness to supply-demand imbalances are usually prioritised according to criteria such as investment risks and economic certainty/motivation, existing technological readiness, geological knowledge and understanding of potential new deposits, research and development capacity, or health and safety regulations, among many others. These variables determine the amount of time required by these responses to restore the balance in the supply chain and are therefore the key to improve our capacity readiness, as shown in the following pages.

Capacity readiness through geological understanding

Although resources of many critical metals may be relatively large and widespread in the Earth's crust, the production concentration which is characteristic of a number of these materials presents risks to primary supply that concern end-users. This may be manifested as market domination by a single supplier, or by groups of suppliers who are geographically-concentrated on giant deposits (such as the South African Bushveld Complex). This concentration, along with inherent uncertainties relating to future demand for individual critical metals, seem to present considerable barriers to aspiring new entrants who might otherwise contribute to a more diverse and resilient primary supply system.

Evidence gathered during the expert panel week indicates that some of the capacity readiness issues associated with, the development of, alternative critical metals resources can be mitigated to a considerable extent through co-production of critical metals with other critical metals, or with other industrial and/or precious metals. Co-production spreads commercial risk by avoiding over-dependence on production of a single critical metal in a relatively small market. Crucially, it offers the possibility of a more flexible and lower risk approach in responding to rapid fluctuations in demand, and therefore price, where viable processing routes are in place.

An understanding of the controls on element sequestration and thus on the ore mineralogy determine the availability of appropriate processing routes, which is vital to the evaluation of critical metal-bearing deposits. In order to determine the critical metal deposits that might be most fit for co-metal production, research is needed that elucidates:

- The geological processes that produce variations in co-metal/mineralogical combinations, such that co-metal ore type domains can be incorporated into regional geological models, which in turn facilitate predictive models for exploration and more robust resource estimation.

- Use of the mineral chemistry and mineral associations/relationships of co-metal ore types within deposits to examine deposit suitability for a more responsive supply and to develop a broader understanding of crustal stocks

- Geometallurgical models for mineral processing based on examination of (1) disaggregation and liberation of the target mineral(s), and (2) identification of optimised or novel mineral processing routes (see next section).

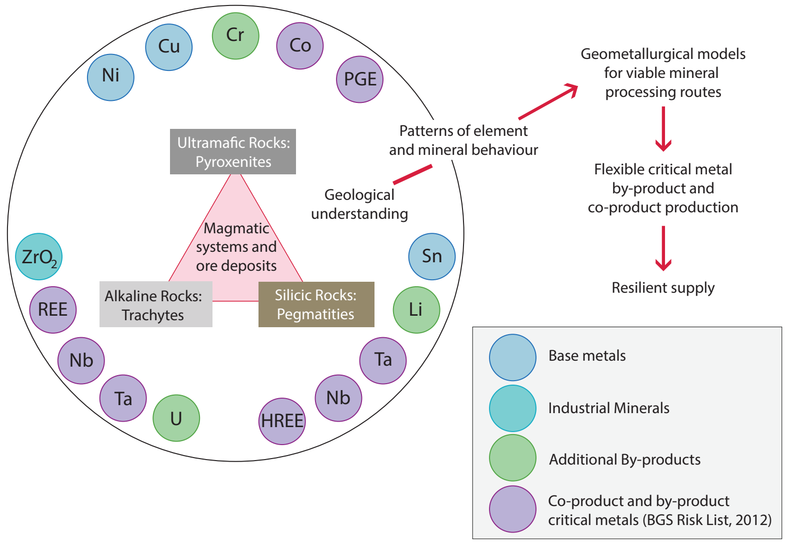
The critical metal co-product associations that we have identified as most adaptable and having the greatest potential for resilient supply are those associated with rocks that formed in three different types of magmatic (molten or igneous rock) system.

- Co and PGM critical metal co-production from copper-nickel ore deposits in magnesium-rich magmatic systems.

- REE co-production with Zr, Hf, Nb, Ta and Y from alkali-rich (trachytic/syenitic) magmatic-fluid systems, where the REE profile is more likely to be enriched in HREE relative to calcium and/or magnesium carbonate-rich (carbonatitic) systems.

- REE and Li co-production with various metals including Nb, Ta, Zr, Y, and Sn in rare-element pegmatites (very coarse-grained igneous rocks).

One objective of the geological research is to understand the reasons for, and thus the characteristics of, elemental and mineralogical couplings in polymetallic critical metal deposits to support capacity readiness through improved exploration, extraction and mineral processing. The geological processes that concentrate the critical metals in host rocks of magmatic origin relate to how these systems cool, crystallise and interact with fluids within the magma and surrounding rocks, and how they react with weathering processes when they are exposed at the Earth's surface.We will select case studies of the magmatic systems that encompass these processes, and represent the best opportunities for the resilient co-production and by-production of critical metals such as PGE, Co, Nb and HREE. We will use state-of-the-art analytical techniques to investigate the variations in mineral associations, textural contexts and mineral chemistry that can be attributed to the various processes. The changes in mineral composition, association and grain-size distribution that arise from each stage of crystallisation, or remobilisation, dictates the geometallurgy of critical metal deposits which will have consequences for the selection, and viability, of alternative processing routes.



Pertinent examples of the geological systems that control the occurrence of co-product and by-product commodities

The second objective of the geological research is to broaden out from the case studies to investigate methodologies for deriving data on crustal stocks of critical metals which might be accessible as co- or by-products. This research would be informed by both the geological case studies linked to magmatic rocks, and the co-investigation into better mineral processing (see next section). Existing published statistical and spatial information will also be used in the development of resource estimates, contributing to critical metal capacity risk and readiness assessments and feeding quantitative data into the left-hand entry to the Sankey diagrams. For example, estimation of cobalt and PGE resources which might be derived from lateritic nickel production. This strand of research could encompass investigation of other metals on the NERC list and could also expand to include attempting a similar approach in estimating secondary resources.

Capacity readiness through better mineral processing

The global mass-flow maps of In, Nb, PGMs and Co in pages 2-3 show that metal losses during beneficiation and refining are disproportionally high compared to losses from the rest of the lifecycle, reducing critical mineral availability. Two complementary research pathways stand out among the capacity readiness enhancement alternatives to address this issue:

- The first research pathway continues the research into the geological formation and chemistry of mineral deposits from the previous section, to develop geometallurgical models for mineral processing, using investigations of mineralogical understanding to examine disaggregation and liberation of ore mineral, and identification of viable mineral processing routes. This research is particularly important for rapidly identifying geological deposits that are amenable to economic exploitation, and targets specifically new mines and addition of co-production for strategic minerals to existing operations.

- The second research pathway focuses on characterising the physical, technological and economic factors that govern existing ore processing methods in order to understand the optimisation potential. This will require engaging with the relevant stakeholders to understand the financial drivers, and the process and technological shortcomings. This pathway targets enhancement of the production and reduction of losses of strategic minerals from existing mining operations.

The two research pathways share a common starting point: a deep review of processing routes for strategic minerals based on their mineralogy. It is necessary to investigate which process technologies minimise material losses during various ore co-processing and metal refining routes and, from a sustainability point of view, which combination has the smallest environmental footprint. This review will include all of the key strategic metals identified by the UK's Natural Environment Research Council (i.e. Li, V, Co, Te, Se, Nd, In, Ga, HREE, C, Nb and PGMs) and additional elements of interest for the project stakeholders. It is envisaged that this review will be the first outcome of the project, and will be published as a monograph and online resource.

For the first research pathway, the process review will be followed, uniquely, by a novel process classification methodology based on For the first research pathway, the process review will be followed, uniquely, by a novel process classification methodology based on geometallurgy. This will allow multi-criterion process selection and evaluation based on co-production of minerals, environmental constraints and economics.

The co-production of strategic minerals with other metals or minerals clearly brings resilience to the supply chain. However, it also places significant constraints on process selection. For example, it can be envisaged that two metals are processed independently most effectively by incompatible process routes (e.g. cyanide leaching following sulphuric acid treatment that would produce poisonous cyanide gas). If co-produced, the optimal route for the combination of metals is likely to be different, with more complex physical processing, chemistry, and environmental constraints.

The process classification methodology will integrate the geological and mineral processing knowledge to determine and recommend viable co-production options. Multi-criteria decision analysis (MCDA) will be used as the basis for identifying complimentary co-production pathways and robustly eliminate non-viable options given a particular geometallurgical scenario. The MCDA framework will give a rigorous methodology for capturing the processing opportunities and constraints that were learnt from the review, and to integrate that information with the geology and mineralogy of the deposit. Further, the MCDA allows sensitivity analysis of the alternatives, transparency of decision-making and traceability. This will be implemented as an internet-based geometallurgical resource.

For the second research pathway, the strategic metal process review, together with stakeholder engagement, will determine the potential and appetite for increasing production from existing operations. A striking result from the Sankey diagrams is that, for Niobium, Indium and Cobalt, processing losses are significant, all of the order of 50%. Production rates of these metals therefore can be increased significantly, and without developing new mines, if these losses can be reduced or eliminated. For Indium, for example, stakeholder engagement will identify reasons for Indium-containing Zinc not being sent to Indium-capable refineries, while the process review will yield the economic potential for retrofitting Indium extraction to existing Zinc-only refineries. This de-bottlenecking of the existing supply chain has the greatest potential for reducing strategic metal shortages in the short- to medium term.

It must be emphasised that it is necessary to follow both these research pathways, as they target both the present production and the future potential. Both are underpinned and are dependent on the geological research into these unique deposits.

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The references contained in this section correspond to the main data sources employed to build the four Sankey diagrams shown on pages 2-3. Further details on how these diagrams have been constructed will be published later on in the form of an academic paper.

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