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A framework and decision support tool for improving value chain resilience to critical materials in manufacturing

Liam Gardner and James Colwill 

Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Loughborough, UK

ABSTRACT

Certain non-energy materials have been identified as being critical to the manufacturing sector and wider economy due to having a high risk of supply disruption combined with high economic importance. The criticality of specific raw materials is becoming increasingly acute as the escalating use of resources is driven by an increasing global population. Critical materials are vital elements in the value chain yet their supply risk may often be ineffectively addressed by traditional supply chain management strategies. Most research to date has been focused at a national or industrial policy level thus many manufacturers are unaware if their operations are at risk from critical materials at a product level. This paper presents a framework that takes a systematic approach to identifying, assessing and mitigating risk associated with critical materials bilaterally along the value chain to facilitate manufacturers in the identification, assessment and mitigation of critical material supply risk. This paper also describes how the framework can be facilitated for application in industry through preliminary design specifications towards a development of a decision support tool.

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Critical materials; resilience; sustainability; supply chain; sustainable value chain; risk management

1. Introduction

This research is focused upon improving the resilience of manufacturers with regards to critical materials (CM) through the formulation of a framework and its application through the specification and preliminary design of a decision support tool. This paper combines and extends upon the research presented in two previous conference publications by Gardner and Colwill (2016a, 2016b). This paper starts by defining resilience within the context of the research and then presents a brief description of what critical materials are and why they pose a risk to manufacturers. From a review of current research in this area there is an apparent lack of awareness by industry with regards to potential CM risk at a business or product level (Jin, Kim, & Guillaume, 2016; Mieke, Schneider, Baaij, & Bauernhansl, 2016). Traditional risk and materials management practices are focused upon

CONTACT James Colwill  j.a.colwill@lboro.ac.uk

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upstream supply risk and usually do not incorporate CM resilience bilaterally along the supply chain (Ho, Zheng, Yildiz, & Talluri, 2015; Tomlin & Wang, 2011). Previous research by Lapko, Trucco, & Nuur and Gardner and Colwill highlighted the need for improved business support for manufacturers to determine if they are exposed at a product level to the risk of interrupted supply of these critical materials (CMs) (Lapko, Trucco, & Nuur, 2016). This paper aims to provide a systematic approach to identifying and quantifying this risk via practical implementation of the framework to enable manufacturers to systematically address CM risk.

1.1. Supply chain resilience

Resilience is a term whose exact meaning can vary depending on its application. In the 'Unified Guidelines for Resilience' the concept of resilience is closely associated with 'the capability and ability of an element to return to a stable state after a disruption' (Bhamra & Burnard, 2010). This definition of resilience does not drastically change when applied to organisations, thus in the context of this research, resilience is defined as the ability of a manufacturer to return to a stable state of normal operating practices or business-as-usual after turbulence or discontinuation in critical material supply (Bhamra, Dani, & Burnard, 2011). Resilience is also a fundamental component of sustainability; to be sustainable a manufacturer must ensure both a reliable supply of all the necessary materials required for production, and sustain the market demand for its products (Christopher & Peck, 2004; Cooper, Lambert, & Pagh, 1997). It is these two principles that the framework and tool aim to address by supporting greater resilience to critical material supply disruption, both up and downstream to the manufacturers operation.

1.1. Critical materials (CM)

Materials are an essential input for all manufacturing operations and maintaining a reliable and consistent supply is fundamental to its success (Tiess, 2010; Zsidisin, Ellram, Carter, & Cavinato, 2004). Any essential material required by a manufacturer can be thought of as critical to that operation and there is no universally agreed definition of 'criticality' or method for its assessment (Graedel & Reck, 2016; Lloyd, Lee, Clifton, Elghali, & France, 2012). However, the term 'critical material', as used in the context of this research, does have a specific meaning. The EU Commission in their 2010 and 2014 reports on critical materials define a material as critical 'when the risks of supply shortage and their impacts on the economy are higher compared with most of the other raw materials' (European Commission, 2014a; European Commission, & Group, 2010b). Thus material criticality in this context is a relative term and will vary according to the economic priorities and circumstances of a particular region or country in which the company operates (Glöser, Tercero Espinoza, Gandenberger, & Faulstich, 2015; Habib & Wenzel, 2016). Many regions or nations such as the EU, Japan, South Korea and the USA have assessed materials using various economic and supply risk factors to create 'critical material' lists specific to their unique circumstances (Barteková & Kemp, 2016; Wrighton, Bee, & Mankelov, 2014). Whilst the specific materials listed will vary they all share the common characteristics of being generally used in small quantities yet being vital in manufacturing value chains and concurrently hard to substitute or eliminate (Erdmann & Graedel, 2011; Peck, Kandachar, & Tempelman, 2014). The

criticality of a material will also vary over time due to the dynamic nature of supply and demand (Knoeri, Wäger, Stamp, Althaus, & Weil, 2013); i.e. Tantalum was assessed as being critical in 2010 but not in 2014 by the EU (European Commission, 2010a, 2014a). This means that any management strategy and associated frameworks and tools should allow for a dynamic rather than a static approach to identifying critical material risk. At a national level the problems of CM supply are likely to become more acute as demand increases. This is partly due to general economic and population growth but more specifically due to the growth in digital, low-carbon and clean technologies that employ them (Grandell et al., 2016; Rabe, Kostka, & Smith Stegen, 2017; Speirs, Gross, Candelise, & Gross, 2011). The problem of material criticality is further compounded by increased globalisation of material supply and value-chains where an event such as a manufacturing plant fire in one location may propagate significant supply disruption on a global scale (Dos Santos et al., 2017; Handfield & McCormack, 2008). For example, Sony Ericsson's \$400 million loss in 2000 after a fire at a semi-conductor manufacturing plant (Ho et al., 2015). In addition to globalisation, a number of other factors can affect the criticality of certain materials, these include:

1.2.1. Geographical concentration of raw materials

Sometimes it is not the abundance of a mineral that determines its supply availability, but gaining effective access to it at a price that is both economically and politically viable. As countries develop they look to maximise the value of their natural resources, by exporting finished products rather than ores or even refined materials (Hayes-Labruto, Schillebeeckx, Workman, & Shah, 2013; Klossek, Kullik, & van den Boogaart, 2016). A recent example of this has been the control on exporting Rare Earth Elements from China, including taxes and quotas on Rare Earth Elements (Sprecher et al., 2015; Wübbecke, 2013).

1.2.2. Technological advancement

Many of the new technologies being developed exploit the properties of CM to give greater efficiency and performance improvements. This is particularly pertinent in the 'green' sector through low energy consumption/co₂ emission products (e.g. electric cars) and renewable energy technologies, such as wind and solar power generation. As the global drive to reduce carbon emissions increases so does the demand for these technologies, both in developed and emerging economies, putting further stress on these CM resources (Nansai et al., 2015; Smith Stegen, 2015).

1.2.3. Future demand forecasting

Due to a combination of population growth and economic development it is predicted that by 2030 there will be an additional 3 billion consumers compared to 2010 levels. As a consequence demand for CM is predicted to rise by over 250% based on current consumption trends (Kharas, 2010; Reisen & Organisation for economic co-operation & development, 2010). However, with rapid technology and material development the future demand for CM can change quickly and has proved difficult to predict with any certainty (Alonso et al., 2012; Chen, 2011).

1.2.4. Changing legislation

Issues with supply, such as the shutting down of illegal mining operations, is another major factor that could limit availability in the future. This is likely to become increasingly influential as new environmental and human-health legislation of mining operations is implemented and competition for land and other resources increase; the nexus challenge (Hong, 2006; Sharmina et al., 2016).

1.2.5. Macroeconomics and climate change

Disruption to supply distribution and production can result in dramatic price fluctuation. This includes both natural and man-made disasters such as conflict materials, terrorism, social unrest, war, earthquake, tsunami and nuclear catastrophes. The flooding in Japan and Thailand in 2011 had extremely serious short and longer term consequences for international electronics and automobile manufacturing, as illustrated by the case of Toyota, where the disaster resulted in production of 40,000 vehicles being dropped costing \$72 million per day in profits (Baldi, Peri, & Vandone, 2014; Ho et al., 2015).

1.2.6. Co-production of materials

The production or extraction of some critical materials is dependent upon the production or extraction of another material e.g. tellurium is produced as a secondary product from copper refining with molybdenum, rhenium, and selenium also from copper ores. This means that if demand for copper falls then production of all the materials is reduced regardless of their individual demand. Other examples include Yttrium which is associated with iron ore extraction in Northern China, germanium and indium from zinc ore; rhodium and ruthenium from platinum group metal ore and gallium from bauxite (Bustamante & Gaustad, 2014; Nassar, Wilburn, & Goonan, 2016; Peiró, Méndez, & Ayres, 2013).

1.2.7. Dissipative losses

The low recycling rates of many CM means that they are lost when the product is disposed of. This is mainly due to the relatively small quantities of CM used in the host product such as additives to improve the performance of another material. With the CM making up such a small percentage of the finished product the cost of its recovery, despite having a high commercial value, is undesirable both economically and environmentally (Chancerel et al., 2013; Zimmermann & Gößling-Reisemann, 2013).

1.2.8. Temporal demand and supply imbalance

The dynamic and fast-paced changes in demand for certain CM often cannot be matched from the supply side due to factors such as the long lead times in setting up mining and other required extraction process. Also the large investment required would be difficult to justify due to the unpredictability of future demand. (Chen, 2011; Haque, Hughes, Lim, & Vernon, 2014).

1.3. Supply risk management

As supply chains have become more efficient and leaner driven by economic and sustainability objectives this has often required a trade off with regards to vulnerability. It has been shown that organisations with a well-defined supply chain risk management policy outperform other organizations that do not (Waters, 2007). However a study by Deloitte showed that 45% of 600 Supply Chain and C-Level executives ‘felt that their supply chain risk management programs were only “somewhat effective” or “not effective at all”, while a mere 33% used risk management approaches to proactively and strategically manage supply chain risk based on conditions in their operating environment’ (Manuj, Esper, & Stank, 2014). It is argued that traditional supply chain management practices may be ineffective in mitigating CM risk as standard free market conditions may not apply due to geopolitical factors such as quotas or sanctions (Massari & Ruberti, 2013; Tukker, 2014). Furthermore traditional supply risk management strategies such as stockpiling or multiple suppliers may well prove ineffective for CM requiring other strategies and business models such as closed loop and product service systems to ensure both a resilient and sustainable supply chain (Govindan, Soleimani, & Kannan, 2015; Ziout, Azab, & Atwan, 2014). The majority of research on material supply risk has focused on upstream supply from the manufacturer (Ghadge, Dani, & Kalawsky, 2012; Ho et al., 2015). However, risks downstream along the value chain, where critical material supply disruption to a manufacturer’s customers may impact directly upon the selling of goods already manufactured, appeared to be generally neglected (Ho et al., 2015; Vallet-Bellmunt, Martínez-Fernández, & Capó-Vicedo, 2011). If manufacturers are to increase their resilience to CMs they must first be aware of all the potential risk and then employ an effective way of assessing and mitigating these risks (Gunasekaran, Patel, & McGaughey, 2004; Pfohl, Köhler, & Thomas, 2010). Previous research highlighted the apparent lack of awareness by industry of the potential risks posed to manufacturers at the product level from CM supply (Lapko et al., 2016). Most research to date regarding CM supply risk has been focused at national policy or industrial systems level (Jin et al., 2016a; Miede et al., 2016). Factors including large datasets, the complexity of the supply chain, the potential for direct and indirect use of CMs both up and downstream, and the specialist knowledge required to gather and interpret the information on CM supply chain risk have highlighted the need for a decision support tool to enable a non-specialist within a manufacturing operation to effectively identify, assess and mitigate CM supply risks (Ghadge et al., 2012). The research presented in this paper addresses this need, proposing a framework and outline decision support tool for use in industry.

2. Framework Summary

The framework presented in this chapter provides manufacturers with a systematic approach for undertaking risk assessment for the whole, or part of, a manufacturing operation with regards to the disruption to the supply of critical materials within its value chain and to then support the effective management and mitigation of these risks. The framework was developed in line with well-established assessment methodologies such as those used in LCA and Lean Manufacturing (Klinglmair, Sala, & Brandão, 2014; Mancini et al., 2014). The requirements of the framework from the point of view of the CM risk identification, assessment and mitigation were deduced through a review of academic literature and state-of-the-art industrial practices. Primary data about the design requirements from the point of view of the tool ‘user’ i.e. a manufacturer, was scarce in the literature so was collected

directly from manufacturers via questionnaires and interviews (Gardner & Colwill, 2016a). The framework has five phases as illustrated in Figure 1. The five phases are summarized as follows:

2.1. Pre-phase

The goal and scope of the project is defined and roles and responsibilities are assigned. It is also this phase where the product lines to be assessed are defined – scope.

2.2. Phase 1

This phase identifies where CM are used in the manufacturer’s product range. In addition risks related to CM availability both upstream and downstream to their operation should also be considered.

2.3. Phase 2

This phase takes the results from phase 1 (products identified as being at risk from CM supply failure) and combines this with the company’s own production and business data on the identified products such as sales forecasts and other management data. This Phase provides information for analysis on the potential CM impacts to specific product lines over time.

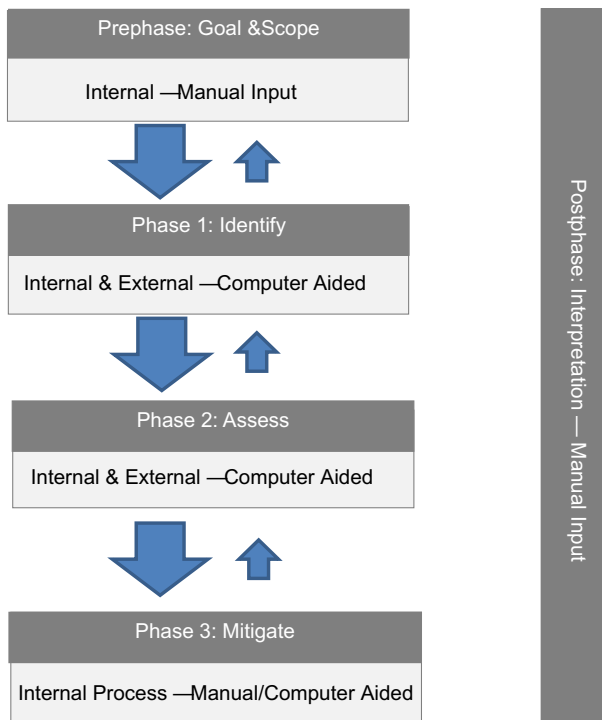


Figure 1. Framework with technical solution for each phase. Adapted with permission from (Gardner & Colwill, 2016b).

2.4. Phase 3

The manufacturer uses the information generated in the previous phases to identify the optimal mitigation strategy for each individual CM risk.

2.5. The post-phase

This runs in parallel with the other phases and continually monitors' changes to input data and warns the user when a significant change to the output information has occurred that could require acting on.

3. Decision-support tool requirements

To enable the facilitation of the framework by manufacturers, a decision-support tool has been conceived and the preliminary design requirements have been specified and developed. This section outlines the tool design and describes the data process-flow for a full iteration of the tool through each of the phases as illustrated in Figure 2.

3.1. Tool design overview

The tool design enables the facilitation of all requirements of the framework through incorporation of the five phases described in section 2. The tool also meets the needs of the user in areas including ease-of-use, compatibility and integration with existing risk and value-chain management policies. The mitigation phase should be incorporated into business continuity planning with triggers from the output of the assessment phase. The overarching process flow is illustrated in Figure 2 showing the flow of information from the pre-phase through phases 1 and 2 to Phase 3. The Post-phase runs in parallel with each of the other phases and provides a constant monitoring and evaluation of changes in the data inputs used.

3.2. Tool user requirements

In the preliminary design of the tool the first stage was to consider the most appropriate method for implementing and supporting each activity in each phase required by the framework. Figure 1 illustrates the original framework diagram developed in previous research (Gardner & Colwill, 2016a, 2016b) with a tool design overview that provides a proposed technical solution for each phase. The user requirements established for the decision support tool require that it must integrate into existing risk management and strategic planning processes and allow phased implementation.

3.2.1. Phased implementation

Phased implementation means that rather than assessing all product lines at once, product lines may be assessed individually or as groups over a predefined scheduled period. This enables implementation of the tool across a portfolio of product lines on a timescale set by the manufacturer. Phased implementation allows any staff time and resources required for the tool implementation to be managed as directed by the user. This is one aspect of the tool that addresses the concerns of potential users of the tool about creating additional

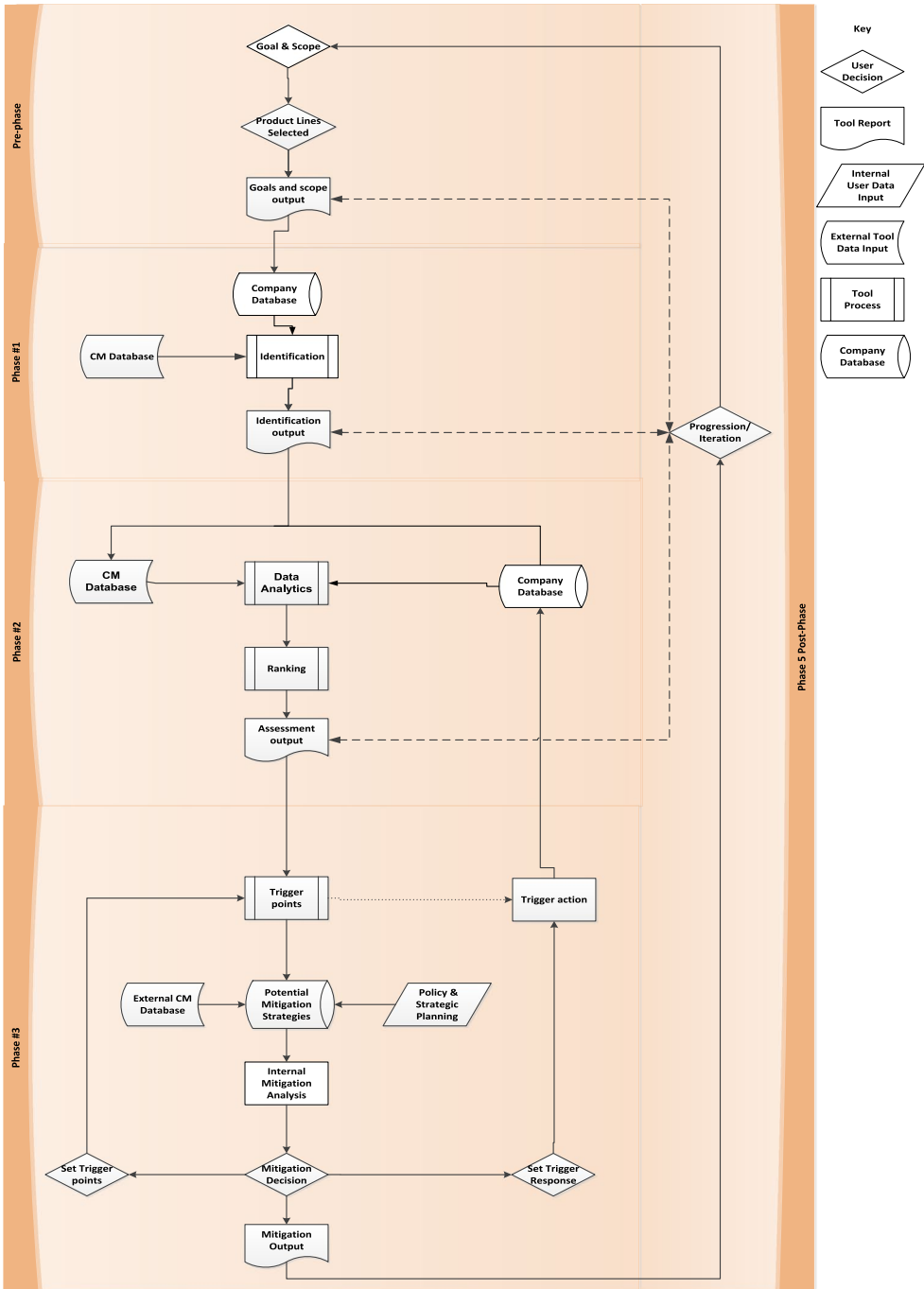


Figure 2. Tool process and dataflow diagram.

workload as identified in previous research by Gardner and Colwill i.e. issues specifically concerning for smaller businesses with fewer staff and resources. A key aspect to phased

implementation is the strategic prioritisation and selective assessment as described in the next sections.

3.2.2. Strategic prioritisation

This section describes strategic prioritisation in the assessment of multiple product lines by the tool. Strategic prioritisation of a specific, or groups of, product line(s) mean the manufacturer can choose in which order the product lines are assessed by the tool. This allows those product lines identified as a 'primary concern' or 'high value' to the business to be assessed first during tool implementation so that resilience may be increased in an optimum temporal capacity i.e. addressing the largest potential risks first so that the largest potential improvements in resilience may be obtained first thus allowing the fastest relative increases in overall resilience. Product lines may be prioritised in a number of ways by the user such as by relative sales value, turnover, profitability, or by key accounts or key customers. Corporate strategy for future market expansions, new product development, product line reductions, obsolescence or cessation of product lines should also be considered by the user at this phase.

3.2.3. Selective assessment

Once prioritisation has taken place the user may progress to selective assessment of product lines. The manufacturer can select a single product line or a bespoke group or multiple groups of product lines for assessment for the tool. This may be done as part of a phased implementation of the tool or selective prioritization as described in the previous sections. Alternatively the manufacturer may choose to select certain product lines for particular attention for sensitivity analysis or scenario planning.

3.3. Tool data requirements

3.3.1. Databases

Electronic data is a key component used by the tool to allow information to be uploaded and processed. There are two distinct types of data used by the tool in phase 1. The first is the *CM Databases*; this contains a list of terms relating to the critical material terminologies and abbreviations. The CM datasets are managed centrally by the tool provider and may be downloaded by the tool/user. The second type, *Company Databases*, contain information relating directly to the manufacturing operation and are managed by the manufacturer. The software for implementing this phase of the tool is Microsoft Excel. This was selected as it meets all the functional requirements for data management required by the tool and is easily available and widely used thud should be compatible with other management software used by manufacturers. Additionally SQL may be utilised with Microsoft Excel Macros for inputting and updating data from external sources.

3.3.2. CM datasets

CM datasets are preloaded into the tool. They are sourced and updated from the best available resource at the time of implementation and review. This research uses the EU reports 2010/14 (European Commission, 2010a, 2014a) and the subsequent data and literature available through the references provided in the report (European Commission, & Group, A. W., 2010b). However, other sources of CM information may be used to populate the

external databases depending upon the geographic location of the manufacturer. The tool allows the user to select the most appropriate CM data for their situation e.g. EU data or UK data for a UK-based manufacturer or USA CM data if the user is based in the USA etc. An example of some of the main types of CM data required is illustrated in Table 1. The CM databases must be maintained, reviewed and updated over time to ensure up-to-date data is available for the tool. This data can be automatically updated in real time through linking the databases directly to the database identified as the source for every data point or group.

3.3.3. *Company databases*

Company Databases must be populated and maintained by the user. This ensures that the data relating specifically to the manufacturers own unique circumstances will be captured by the tool. The database must be maintained and any changes including changes to suppliers and customers must be updated if the tool is to work effectively. The tool will allow existing electronic company databases like Enterprise Resource Planning (ERP) systems such as SAP to automatically populate and update the Company Databases. The scope of the databases and exactly when, why and how they will be updated should be determined by the manufacturer during the initial Pre-Phase. This could include databases covering either the entire operation or alternatively just selected product lines or key customers. There is also the option to create databases for potential or future products, for changes in process to aid in design and management decision-making, for new lines or for changes to current operating procedures during business continuity management. The information required to be provided by the user and input into the Company Databases is listed in Table 2.

3.3.4. *Reports*

Electronic reports are generated on the completion of each phase giving 4 reports in total; Pre-phase Report, Phase 1 Report, Phase 2 Report and Phase 3 Report. An example Phase 1 report is illustrated by Table 3. A key aspect is that data from the report can be checked for accuracy and anomaly as part of the Post-phase interpretation. The reports allow all information obtained at each phase to be documented and used by the manufacturer to inform risk-management and business continuity planning.

4. Tool preliminary design and specifications

This section describes the dataflow through a complete iteration of the tool as illustrated in Figure 2. As described above the tool uses information from internal and external databases to systematically identify potential CM risks, allows assessment of these risks and provides decision support for mitigation of these risks.

Table 1. List of major categories of external data required.

<i>External data required:</i>
List of Critical Material names and pseudonyms
Known uses in products for every CM
Known uses in process for every CM
Known uses in components for every CM
Known uses in capital equipment
Known uses in consumables
Known pseudonyms for every category
External supply risk factor for each CM

Table 2. List of internal data requirements for each product line.

Data required for every product line:

- Complete list of required materials (Bill of Materials)
- Component specifications for each component
- Matrix of linked products
- Supplier list for each material including key account info
- Client/customer list for each product including Key Account info
- List of capital Equipment used
- Consumables Related to Capital Equipment used
- Manufacturing Processes utilized internal and external

4.1. Pre-phase: goal and scope

It is at the Pre-Phase that integration of the tool into the Standard Operating Procedures for Risk Management and Business Continuity Planning must be ensured by the user. This includes responsibilities, timelines and dates set for alternative or future iterations of the tool or reviews of data relevant to the tool. This may include provisions for periodic reviews and procedures set in place for tool iterations in response changes to the manufacturer's product line portfolio such as the addition of new product lines or changes to, or cessation of, existing product lines.

4.1.1. Pre-phase data requirements

The tool is capable of being applied to all product lines of a business and this is encouraged to ensure maximum resilience is obtained throughout a manufacturing operation in its entirety. However, to facilitate the flexibility and ease-of-use the tool is designed to be able to be applied to individual or bespoke groups of product lines as desired by the user. This has a number of benefits including enabling phased implementation of the tool, prioritised implementation of the tool, selection of singular or groups of manufacturing lines via relationship to key customers or future business or on criteria such as percentage of sales or turnover/profitability etc.

4.1.2. Pre-phase report and progression

At the end of each phase a report is generated to allow Post-Phase interpretation to be undertaken. All information is to be checked for accuracy and if all criteria are met progression may continue. Any errors, incomplete information or failure to meet objectives set at the Pre-Phase that are detected at this stage means progression cannot continue until they are addressed and corrective action taken before another tool iteration may commence. Thus for this Pre-Phase this means the manufacturer must check to ensure all desired product lines are correctly input to the tool.

4.2. Phase 1: identification

Phase 1 requires the interrogation of large amounts of existing data held by the company in an electronic format against a list of the key words developed for identifying Critical Materials. Materials data from internal sources such as a bill of materials must be cross-referenced against an external database of critical materials and known pseudonyms so that critical materials utilised by a manufacturer are identified. This phase is computer-aided

Table 3. Information provided by the Phase 1 report.

Critical material	Product lines	Modes of impact	Points of impact	Risk
Neodymium (Light Rare Earth Element)	Product A	Raw material directly used in manufacturing of product	Upstream Tier 1 Product A + B	Confirmed A + B
Germanium	Product B	Raw material directly used in manufacturing process F	Material availability	Bill of Materials (link to document) (Supplier 1)
	Product C		Upstream Tier 1 Process F	Confirmed C Bill of Materials (link to document) (Supplier 2)
Gallium	Product B	Component Y known to contain CM	Material availability	Confirmed B Component Y Specification (link to document) (supplier 3)
			Upstream Tier 2 Product B	
Indium	Product A	Component Z known to require CM in its manufacturing process	Component availability	Potential A + C (Component Z = Supplier 1)
			Upstream Tier 3 Product A + C	
Magnesium	Product C	Raw material required for known downstream use of product	Component availability	Potential B + C (Clients 1,2,4,7)
	Product B		Downstream Tier 1	
	Product C		Products B + C Sales risk	
Graphite	Product A	Known use in linked products	Downstream Tier 1/2	Potential A (Clients 3, 5, 6)
			Product A Sales risk	

through widely available spreadsheet software Microsoft Excel. An electronic report of each CM risk identified with links to the associated data is generated at the end of Phase 1.

4.2.1. Phase 1 'identification' data requirements

At Phase one the user must input all the required internal data relating to the product lines selected in the Pre-Phase into internal databases described in Table 2. This can be automated through linking SAP or other ERP software directly to the tool. This data is then processed with external critical material data obtained and input automatically by the tool described in Table 1. The result of this data processing is an electronic report detailing the Phase 1 Identification data and listing each CM risk identified illustrated in Table 3.

4.2.2. Phase 1 CM data

The particular circumstances of the manufacturer such as what nation and region they and their suppliers are located in will determine the best available data selected from external sources for use in the tool. The data used in this paper pertains to the EU report on critical materials however the tool can be uploaded with other region-specific databases e.g. a USA based manufacturer would require CM data for the USA from sources such as Department of Energy reports, or in the case of changing geopolitical unions such as 'Brexit' (the UK leaving the EU) the data would require UK specific data such as from the British Geological Survey Risk List (Commission, 2020; EU Commission, 2014b; House of Commons, & Science & Technology Committee, 2011; Bauer et al., 2010). The tool is designed so that CM data is uploaded and ready to use by the manufacturer however the functionality is there to allow alternative bespoke external data to be selected by the manufacturer to allow for situations unique to their circumstances. Periodic review and update is achieved through automated real-time or periodic updating of the CM Databases linked to the tool.

4.2.3. Phase 1 company data

After all product lines that are to be assessed by the tool have been selected by the manufacturer and input into the tool in the Pre-Phase then for each product-line a list of associated company data is required as listed in Table 3. For each individual product-line a matrix of linked databases is populated with information on the materials, processes, capital equipment and suppliers etc. and also information on the product and clients and linked products downstream. The information listed in Table 2 is obtainable to the manufacturer from various sources such as bill of materials (BoM) for materials and supplier information or customer account information for product sales to customers. Guidance on where to seek the best available information is to be provided through the provision of a Tool User Guide. When implementing the tool for the first time there will be some staff time requirements to populate the various databases. To minimise the time required and make the data input process as easy as possible so as to be in line with the tool design requirements, the tool has been designed to be compatible with the various Excel and Word reports generated by other data management programmes. This means that the tool may be set up so that it needs no further direct updating of data after the initial implementation as it can directly link to the manufacturer's own internal databases through SAP and other ERP-type software. After all selected product lines and associated data have been successfully input into the Company Database the manufacturer confirms the data and a report is then generated by

the tool documenting all the information received. This report should be checked by the manufacturer to ensure every intended product line is present before progression.

After all the required data has been populated into the individual databases a dynamic data-set with cross-linked data points is now available to the user through the tool as illustrated in Table 4. This allows all relevant information to be linked together by the tool and accessed in future phases for processing and report generation. The data from the CM Databases are cross referenced with the data from the Company Databases to check for any potential Critical Material use associated with the product lines. Any confirmed points of impact such as a Critical Material or known pseudonym being identified in a Bill of Materials or a consumable used in a manufacturing process is identified as a ‘confirmed risk’ and links to all the associated data as illustrated in Table 3. Potential points of impact e.g. through a linked product or a known use of the product are labelled ‘Potential risks’ as also illustrated in Table 3.

4.2.4. Phase 1 output and report

Upon completion of Phase 1 an electronic report is generated by the tool containing all the information input and processed. This lists each product line with information on each CM risk identified including the material and point of impact and which suppliers or clients this will impact as illustrated in Table 3. All the data in the various databases are linked for ease of use by the manufacturer so all relevant information is available in spreadsheet form via the electronic report.

Table 3 shows an example report from Phase1. The first column titled ‘Critical Material’ names the critical material identified. The second column titled ‘Product Lines Affected’ lists each product line identified (illustrated with examples Product A, B or C) as having an association with the named CM from column 1. The third column titled ‘Modes of Impact’ states the how the CM relates to that product line. Examples given in Table 3 are illustrative and not an exhaustive list but do show the main ways a CM may impact a product line. Row 2 gives an example of when a CM may be a raw material used directly in the manufacture of a product so that the material forms part of the finished product e.g. neodymium being used to manufacture a magnet. Row 4 gives an example of when a CM may also be required for components that are directly required for the manufacture of a product line e.g. LEDs may be required that are known to contain gallium. Rows 3 and 5 give examples of when a CM may be utilised in a process required to make the product or a component contained in the final product but the material itself does not end up in the final product such as in the case of a catalyst e.g. germanium being used as a polymerisation catalyst in PET plastic manufacturing. Row 6 gives an example of the required data output when a CM is required

Table 4. Table illustrating multiple data-base links.

Product line	A	B	C
Materials required	–	–	–
Internal manufacturing processes	–	–	–
External manufacturing processes	–	–	–
Suppliers	–	–	–
Clients	–	–	–
Capital equipment	–	–	–
Consumables	–	–	–
Names of product and pseudonyms	–	–	–

in the known downstream use of the final product for example when a component manufactured is known to be utilised with another product component that is manufactured by another company e.g. an automotive parts manufacturer whose products are used as a component in conjunction with a magnesium alloy die-cast component part that is manufactured by a different company, to create another distinct product such as a particular model of car further down the value chain. Row 7 gives an example of the data output required when a CM is required for a 'linked' product. A 'linked' product is defined here as a finished product not manufactured by the company itself and which is not a component that goes to create a new product. It is a finished product that is ancillary or complimentary to the original product being manufactured. The fourth column titled 'points of Impact' states how and where in the value-chain the CM impacts the business.

4.2.5. Phase 1 progression requirements

The manufacturer must ensure that all the data required for each product line is correct and complete. All information must be checked against the requirements of the Post-Phase interpretation. If the requirements are not met then progression to the next phase cannot continue before action is taken to remediate and another iteration of the tool may then occur. If all data is complete and the user's requirements are met then progression to the next Phase may continue.

4.3. Phase 2: assessment

This phase takes the results from phase 1 (products identified as being at risk from CM supply failure) and combines this with the company's sales forecasts and management data to provide a dynamic visualisation of the potential impact to the company's business over time (x-axis) as illustrated in Figure 3. In addition the likelihood of the risk of a supply failure for each CM is presented using external CM data. How this risk is forecast to

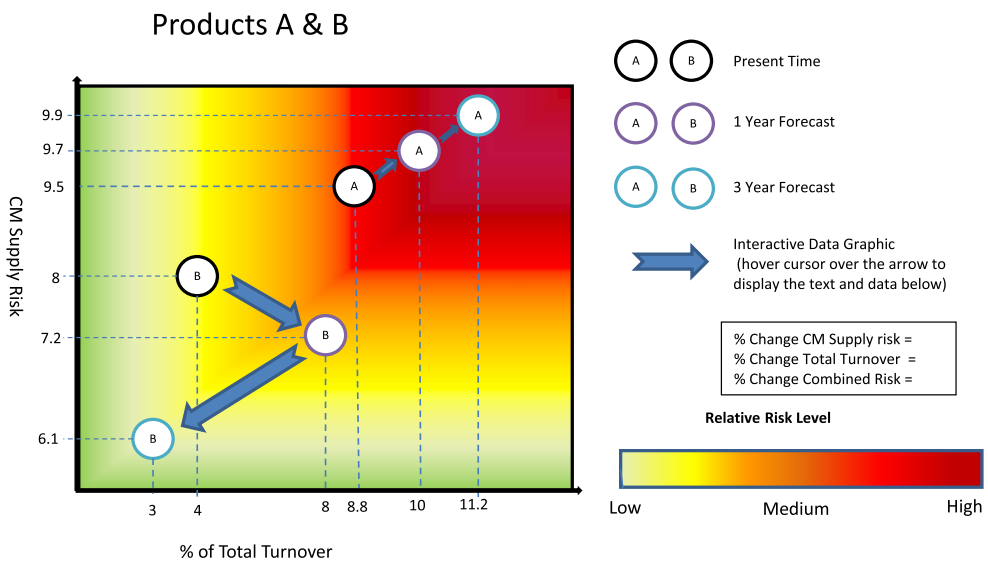


Figure 3. Example of interactive data report from Phase 2.

change over time is also considered (y-axis). By combining these two sets of data both the direction (higher or lower) and the rate of change over time (faster or slower) can also be plotted (Figure 3).

Phase 2 takes the information of identified CM risk from Phase 1 and allows each discreet risk to be assessed and quantified from both an external (CM supply risk) and internal business perspective (percentage of turnover/gross profit/key customers etc. linked to the specific product). In this way Phase 2 allows the manufacturer to address the specific risk to their business by examining potential implications on production of each product line from upstream risks in material, consumable and capital equipment availability and also downstream risks to sales by assessing and quantifying each individual risk.

Phase 2 automatically links the electronic report generated at Phase 1 to a pre-populated CM risk information database containing risk data on every CM identified (Table 1). Upon completion of Phase 2 the tool generates an electronic report as exemplified in Figure 3. This illustrates one type of graphical representation provided by the tool, based on two products, A & B, identified in Phase 1 as having a different CM risk. It shows how the CM supply risk can change from the present scenario to future forecasts of CM supply risk with the example of a one year and three year forecast. Product A sees an increase in both CM supply risk and projected percentage of total company turnover. Therefore the plot for product A moves both to the right along the x-axis (percentage of total turnover) and up along the y-axis (CM supply risk) increasing the potential risk to the company. Product B shows a decrease in CM supply risk from the present to the one year forecast and then from the one year forecast to the three year forecast and so moves down the y-axis. Product B shows a forecasted increase in total turnover from the present to year one and so moves right along the x-axis. However from the one year forecast to the three year forecast the percentage of total turnover actual decreases to lower than present levels so the overall risk to the company increase from the present to year one but then decreases from year one to year 3 to below present levels. The company producing products A and B should be able to determine easily from the graphical format that product A represents a higher risk than product B and should therefore be prioritised. Additional information on the changing risks of products is provided through the interactive element shown by the blue arrow graphics. This was designed so that the user is not confronted by a large amount of detailed data but can access it easily whenever required to enable a more user-friendly interface with the tool. This is just one example of how the tool will provide easy to understand risk data to the user but there are many variations including product specific CM Supply Risk: Gross Profit, rate of risk increase over time etc. Other important features include that both x and y axis are scalable by the user to suit their circumstances meaning that the 'Relative Risk Level' scale (Figure 3) can be adjusted to suit their specific requirements.

4.3.1. Phase 2 progression requirements

The user must check the Phase 2 report meets all the requirements of the Post-Phase. If these requirements are not met then the user must make the required changes and return to the start of the Phase to start another iteration. If the Post-Phase requirements are achieved progression continues to Phase 3.

4.4. Phase 3: mitigation

Phase 3 uses the output from Phase 2 and draws on data from external CM information databases. The Phase 2 electronic report is used by the user to enable formulation of appropriate mitigation strategies and to set trigger points for ongoing risk management. The user decides and sets a value for each trigger point. This allows for scenario planning and contingency planning by the company as trigger points and their corresponding actions are recorded electronically to provide an ongoing risk monitoring facility if and when trigger points are hit. Phase 3 therefore is computer aided but requires manual input from the user to ensure bespoke mitigation actions are implemented.

The user utilises the Phase 2 report to assist in formulating and implementing the optimum mitigation strategy for each CM risk. Mitigation options must be considered by the user with a view to minimising the risk to each product line. Each CM risk identified must be assessed for potential mitigation strategies. External data from a CM databases provide relevant information about the supply risk of each material such as exporting countries, quotas etc. that may impact upon a manufacturers situation. Mitigation may involve collaborating with suppliers and customers both up and down the value chain to improve resilience through reduced material supply risk. A list of generic mitigation options for consideration by the user is provided by the tool such as material elimination or substitution, product design change, operational changes, changes to contracts, possible additional clauses, changes to policy-making, material substitution, business model change–leasing, product service systems, closing the loop, product take back, stockpiling, improved data communication with key suppliers/customers etc. The user assesses the various mitigation options provided by the tool and selects either one of these or a mitigation option of their own creation. When the risk is either eliminated completely, or a sufficiently acceptable low risk is achieved, that particular option should be implemented by the user and recorded in the tool. After implanting each mitigation action each CM risk is reassessed via an automated iteration of Phase 2.

4.4.1. Trigger points and actions

Both the CM Databases and Company Databases are dynamic and will change overtime meaning that any identified risk has the potential to increase or decrease (Figure 3). For each CM risk identified a trigger point is set by the user so that if a risk score at any point reaches the threshold set by a manufacturer a mitigation action is triggered. The trigger point and each corresponding trigger action must be determined and set by the user during the initial implementation of the tool during the first iteration. During every subsequent tool iteration both the trigger point and trigger action for each unique risk must be reviewed and updated accordingly. When a mitigation action is triggered the user must redo phase 3 for the new risk and update its mitigation strategy accordingly. Once completed the system (triggers) can be reset.

4.4.2. Phase 3 outputs and reports

A range of electronic reports can be generated in this phase, combining information from the previous phases with mitigation actions, trigger points and trigger actions. Phase 3 is completed when every CM risk has been either eliminated or mitigated to a risk score that is at a level acceptable to, and set by, the user. Each CM risk must have a trigger point set

with a pre-determined trigger action so the manufacturer can react automatically to mitigate increased risks. All information must be checked against the requirements of the Post-Phase interpretation. If the requirements are not met then progression to the next phase must not continue until remedial action is undertaken by the user. If all data is complete and the user's requirements are met then the user progresses to the next and final phase.

4.5. Post-phase: interpretation

The Post-Phase is part of the iterative design of the tool allowing the user to check the results from each phase before progressing to the next phase. In practice this allows checks and balances with the option to redefine parameters set in each of the phases. If the requirements of any phase are not met it is identified at this point and action must be taken to remediate this before progressing to the next phase. This enables the tool to be sufficiently adaptable and dynamic to allow adjustment in line with changing business policies and strategies and also allows phased implementation by the user. It also allows for refinement and improvements in data entry and risk analysis scoring and weighting in all previous phases after each iteration. At the end of Phase 3 procedures for reviewing and updating of data are considered and implemented. The decisions made by the user during this phase are recorded electronically to ensure an audit trail for each phase being assessed and to sign off a complete tool iteration.

5. Conclusions and future work

A framework was proposed and summarised to allow CM risk to be effectively and systematically identified, assessed and mitigated by a manufacturer. A decision-support tool to allow the practical implementation of the framework by a manufacturer was discussed with details of the design overview with a description of the data process flow through each of the phases of a full iteration of the tool. The major limitation of the tool is reliance on high quality of both the internal and external data. The gathering of high quality internal data by the user will be facilitated through the provision of a 'Tool User Guide' to help the user select best available data.

The external CM data requires updating via an expert source with the responsibility of sourcing the best available data for the manufacturer's location and ensure this is kept up to date. The tool databases are to be maintained remotely with updates to the tool via the internet. The external supply risk data may be obtained automatically from CM risk data sources such as the UK Risk List or European Commission reports via automatic data extraction and data scraping programmes that are widely commercially available. This will enable the CM supply risk data to be translated into a common language such as Comma-Separated Value format that is compatible with ERP systems and most commonly used data management programmes such as Microsoft Excel.

The specifications described will ensure that the tool provides a flexible and effective means of implementing the framework. It allows the integration of existing company's databases to identify direct uses of the critical materials as well as highlighting potential indirect uses or interactions both up and down the value stream. The reports generated at each Phase can be extracted and used within other decision-making processes. It allows risk assessment bespoke to the company to be combined with external materials data for

analysis and report generation. The discrete phases and iterative process allow for experimentation with changes in variables by a manufacturer. The ability for scenario planning has the potential to offer manufacturer's insight into how changes in current circumstances may cause significant changes in risk that may in turn effect the mitigation options available or what is ultimately deemed the most effective or desirable risk mitigation strategy to choose. This research asserts that CM risk may be effectively identified, assessed and mitigated at a product level by manufacturers through the application of a systematic framework via a decision-support tool. The strengths and weaknesses of the framework and tool were assessed and the following conclusions have been drawn:

- Whilst most manufacturers would be aware of materials purchased and used directly, CM are often used in very small quantities to improve the performance of a base material or within components and parts manufactured by third parties. The tool provides an effective means of identifying the use of CM in goods manufactured within the host organisation using existing data held by the organisation. This reduces the time and effort required, avoids human error and limits the expertise in CM required by the investigator.
- If the process is then repeated by their suppliers and customers then the indirect risks can be quantified ensuring the whole supply chain is made more resilient.
- By calculating the magnitude and likelihood of the risk and displaying this graphically either by product, CM or both, the company can quickly identify the most pertinent risk to the business and take immediate action to mitigate the risk in the short term.
- By applying forecasting data for both product sales and CM supply risk, the tool can provide the user with a sliding scale of risk over time that can be used to show the direction and rate of change of risk magnitude and likelihood to allow a more effective long term strategy to be developed in line with the changing business needs and CM market supply model.
- Once a full iteration of the tool has taken place, changes to the base input data can be automatically monitored and the effect of those changes to the current model and predictions calculated. Alerts can then be automatically generated if such changes are significant enough to alter the risk model within previously defined limits.
- The effectiveness of the tool is particularly reliant on the quality of data held in the CM data-set used for discovery and the data held in the CM database used to determine the probability of the CM risk to the company. It is proposed that, as with other databases and datasets used in analysis and assessment (LCA, Antivirus etc.) the quality and comprehensiveness of these will improve as its use and awareness increases and updates are made.
- The tool aims to be as automated as possible by linking data between the company's Enterprise Resource Planning system and externally generated CM supply risk data. A limitation to this automation may be some manual input required to ensure that this data extraction and translation is completed successfully.
- Further case studies are required to establish additional user requirements and the tools compatibility with most commonly used methods, processes and systems.
- The next stage of research is to develop a beta version of the software tool to allow more extensive user testing. This would be validated against results generated from a second analysis applying the framework and tool manually. The specifications for the

beta version would need to fully integrate with different existing ERP tools in compatibility and fully align with aspects such as data integrity and security. The exact design specification of the decision support tool and testing to illustrate usability will be the focus of the next stage of research and will be published in the next paper.

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ORCID

James Colwill  <http://orcid.org/0000-0003-3541-0096>

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