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A framework for the resilient use of critical materials in sustainable manufacturing systems

Liam Gardner^a and James Colwill^{a,*}

^a*Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Ashby Road, Loughborough, LE11 3TU, UK*

* Corresponding author. Tel.: +44 1509 225405; e-mail address: j.a.colwill@lboro.ac.uk

Abstract

A number of materials have been identified by the EU as being critical to their member's economies and manufacturing industries. A material has been defined by the EU as being critical if it is of "high economic importance combined with a high risk of supply shortage". This criticality will become increasingly acute as the escalating use of finite resources continues, driven by growing populations and consumer demand. One group of materials that is listed top on the majority of these „critical“ lists are rare earths, which include the elements neodymium and dysprosium. These are often used in high value, high technology products used in renewable energy, military and aerospace sectors. Whilst most manufacturers would be aware of the direct use of rare earth elements in their products, many may not be aware of their indirect use such as in manufacturing equipment and bought-in components, or further down the value chain in inter-reliant products or consumables. This paper presents a framework for the resilient use of critical materials in sustainable manufacturing systems. The first phase of this three phase framework identifies where, in the value chain of this business, critical material are used. Once identified, the second phase assesses the level of risk to the business based upon the likelihood, frequency and severity of a supply disruption occurring for the critical material identified. The third phase supports the identification and development of suitable mitigation strategies to reduce this risk, including the consideration of factors specific to the business as well as more general ones associated with the type of rare earth and its application. The paper concludes with a case study, based on simulated data, that demonstrates the application of phase one of this framework in a typical manufacturing operation.

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1. Introduction

In this paper a framework to support the resilient use of critical materials within sustainable manufacturing systems is developed and exemplified. Central to this framework is the fundamental principle that in order to manage an activity, process or system, one must first measure it. This basic management principle lies at the heart of this and many other frameworks and methodologies including Life Cycle Assessment, Lean Manufacturing and Risk Assessment [1,2]. The paper begins with an introduction to the concept of sustainability, resilience and critical materials within the manufacturing supply chain. The framework, consisting of five phases (Phases 1-3 plus a pre and post phase), is then

presented and illustrated using simulated data. Finally, the opportunities for applying this framework within manufacturing systems and the additional work required to do so is discussed.

For a manufacturing process to be described as "sustainable" it needs to conform to the notion of "sustainability", a term that is generally accepted to have been first coined in the Brundtland Report where sustainable development is termed as "development that meets the needs of the present without compromising future generations" ability to meet their own needs"[3] Therefore by extension sustainable manufacturing systems could be described as "manufacturing processes that meet the needs of the present

without compromising future generations' ability to meet their own needs". The US Department of Commerce defines sustainable manufacturing as "the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound." [4]. Thus the processes used to sustainably manufacture a product must fit this criteria, however to be a truly sustainable business, the goods and services produced must also fit into this same concept of sustainability and minimise the negative, and promote the positive, environmental, social and economic impacts throughout the life cycle.

Sustainability is generally focused on long-term issues, such as climate change, and cannot be achieved in isolation; although improvements can be implemented at a local (company) level. Sustainability is a Global issue and requires a global response. However, resilience; "the capability and ability of an element (in this case a business), to return to a pre-disturbance state after a disruption" [5] can be implemented in isolation and is generally focused on the mitigation of short-term impacts (e.g. severe weather events such as flooding). In this regard a company can be resilient without being sustainable but not vice versa (e.g. an oil company). Therefore a good business sustainability strategy should also include an aspect of resilience, particularly with regard to disruptions to manufacturing and sales, including those caused by material supply issues.

1.1. Critical materials and Rare Earths

Whilst any material that is essential for normal operating practice of a business could be said to be critical, the term "critical material", as used in this paper, refers specifically to the EU definition taken from their 2010 and 2014 reports on critical materials; "when the risks of supply shortage and their impacts on the economy are higher compared with most of the other raw materials". Two types of risk are considered by the EU in their reports. The first type of risk is the "supply risk" which takes into account the political-economic stability of the producing countries, the level of concentration of production, the potential for substitution and the recycling rate. The second is "environmental country risk" which assesses the risks that measures might be taken by countries with weak environmental performance in order to protect the environment and, in doing so endanger the supply of the raw materials to the EU [6,7].

Of all the materials considered in the EU report, one group of elements collectively termed Rare Earth Elements (REE) were assessed to have the highest chance of supply disruption and have the highest overall criticality of all the materials considered. REE consist of 17 chemical elements, Scandium, Yttrium and the 15 Lanthanides and are sometimes classified further into groupings of heavy REE and light REE [6,7]. For the purpose of this paper, REE will be used as an example of a CM to illustrate some of the factors that can drive material criticality and how this may impact a business' value chain.

One of the major contributing factors to this high potential for REE supply disruption is their relatively high elastic demand coupled with an inelastic supply. Demand for a material can vary due to many factors under normal free-market conditions and this can cause problems in a supply network if the supply of the stated material is for some reason unable to react and change quickly enough to balance the change in demand. REE has already seen a massive increase in demand that is projected to continue and increase due to the proliferation in the number of new products that contain or rely on these materials which is in turn compounded by the very high rate of uptake in volume of these new products around the world [8,9,10] Supply of REE could be described as inelastic due to the fact that it is currently primarily obtained through mining processes that have relatively long lead times, typically taking up to a decade or more before significant increases of production can be realised as additional market supply [6,7,11].

Primary REE extraction has many negative environmental impacts such as ground and water pollution, heavy metal contamination, and the production of radioactive waste which has also lead to health and other social concerns for local populations [13]. This means that there is a risk that supply could be disrupted or limited as steps are taken to try and reduce the environmental impact of extraction – this is a factor of the Environmental Country Risk as discussed. Primary production of REE therefore has many issues and risks associated with it so secondary production through various recycling routes or urban mining must be considered as an alternative material supply. However, in the case of REE recycling rates for end-of-life products is very low at less than 1%. This is due to various reasons including the fact that small quantities are generally used and often the routes, infrastructure and techniques for recovery are challenging and prohibitively expensive making it commercially unviable in most cases [12].

Under normal free market conditions increased demand for a material with a limited supply typically results in an increased market price for that material as more businesses compete for a limited resource by outbidding competitors financially. However in the case of REE and other CMs this usual situation may not occur due to the action of geopolitical factors resulting in scenarios where typical free-market conditions do not occur. Due to the domination of primary REE supply by a single nation, China, political factors can play an enormously significant role in world supply. National industrial strategies such as efforts to consolidate and retain a material value chain within a country can have huge implications for supply especially when production is concentrated in a few areas E.g. a decision to introduce and then increase export quotas by China could mean that the total REE supply for the rest of the world can be dramatically reduced extremely rapidly [9,10,11].

Therefore due to these, and numerous other, often acute and sometimes unique, material supply factors acting upon

CMs, the traditional strategies employed by businesses to address free-market supply issues may well prove to be unaffordable or ineffective in the case of REE and other CMs. To increase business resilience one must first understand the level of risk exposure to CMs, however, many businesses are unaware if they are exposed to this risk anywhere in the value chain and if so, to what degree of severity. Therefore a key area in sustainable manufacturing has been identified – how to optimise business resilience through identifying and assessing exposure to critical material supply risk. The following framework will enable this objective.

1.2. Visibility of CMs in manufacturing and its Value Chain

This section describes the issues associated with the use of CMs in manufacturing and how these can be hidden within the supply chain. CM reliance in the value chain is often not obvious, so understanding if disruption in CM supply may affect a business, to what extent, and where exactly in the value chain this is likely to occur is vital to allow effective risk management and mitigation strategies, hence need for the systematic approach and framework Phase One. As the risk of CM supply disruption is determined as very high for companies in the EU [6,7] then a company must determine how severe such an event would be to its normal operating practice. For some companies this may be very easy to determine as the use of a stated CM may be very visible e.g. for a company that directly uses a specific CM in their manufacturing process and whom know it cannot be easily substituted should easily identify that a supply chain disruption would have a severe impact on their business and therefore it would be good business practice to proactively prepare for such an event to mitigate the potential damage.

Due to the nature of CMs such as REEs generally having unique physical and chemical properties they are usually difficult to substitute for another material without loss of function – this is a key factor in why their supply disruption cannot be easily solved by simply replacing them with another similar material. CMs are often used in very small quantities as additives sometimes being referred to as “vitamins” to boost performance. These small quantities combined with the unique yet ubiquitous nature of the materials in such a wide variety of processes, components and products [8] is just one factor that means it can be very difficult for an individual business to know if their value chains actually utilise a CM or not. It is important to note that a CM may be critical in the supply chain but not present as an actual material used in a product itself, but through utilization in a critical process somewhere along the supply chain. This means a company may be reliant on raw materials or components that contain no CM but are still reliant on CMs for their production. This is another way that the potential effects of CM supply disruption may be „hidden“ from a business.

Traditional supply-chain management has generally focused on up-stream materials supply i.e. the flow of material from the source to the gates of the factory. This is just as important in the case of CM resilience and the challenges of

obtaining reliable data on material flow through the supply chain remains the same. It may be relatively easy and practical to obtain material information from a direct supplier, however, it is usually the case that at each tier of supply moving further away from a business along the supply chain it can prove increasingly difficult to obtain reliable material supply and consumption data.

An area that appears to be much less studied are the downstream risks associated with material supply disruptions. A company may be able to adequately process and obtain all the required CM's to make a specific product, however, if that product is somehow reliant or associated with CM's further down the supply chain then that product and associated business may still be at risk from CM supply disruption. A simple example of this may be a component manufacturer whose components do not contain CM are then assembled into a finished product that utilises a CM e.g. a wind turbine blade manufacturer. Other situations include scenarios where a product may not rely directly on CM in the value chain but may be ancillary or complementary products to CM-reliant products and thus may still be significantly affected by CM supply disruption.

2. Framework

This framework sets out a systematic approach for undertaking a risk assessment of whole or part of a manufacturing operation to the impacts associated with disruption to supply of critical materials within its value chain and to support the effective management and mitigation of these risks. The framework described in this paper has similarities with well established assessment methodologies, as used in LCA and Lean Manufacturing. The first phase defines the goal and scope of the project, the second phase develops an inventory based model of the company's value chain that quantitatively and qualitatively identifies the nature and scale of the critical material use and the potential impact on the business in terms of lost production and sales. This allows each of the CM's to be prioritized, in terms of their business importance.

An assessment is then carried out to gain a deeper understanding of the current general risks associated with the supply of the material and any unique risks associated with its particular application and use. The fourth phase uses the outputs from the earlier phases to develop suitable risk avoidance and mitigation strategies to improve the overall resilience and sustainability of the business. The fifth phase is an interpretation phase that runs in parallel with each of the preceding phases ensuring that the outputs of each phase are in line with the aims and objectives defined at the beginning of the project, as highlighted in Figure 1.

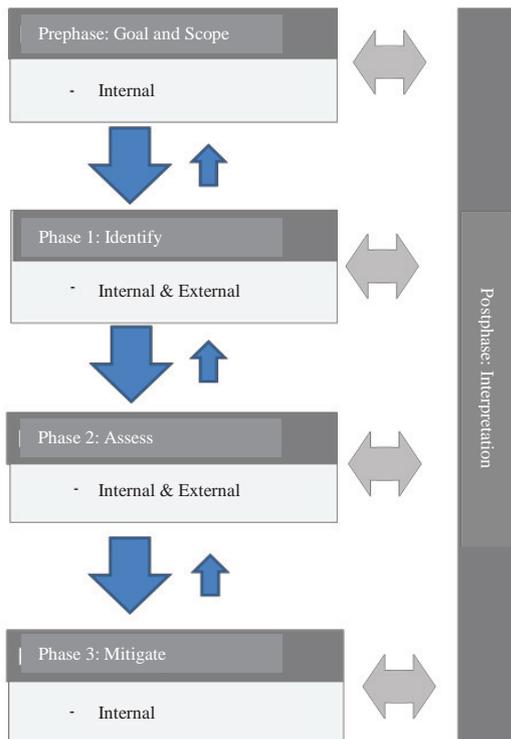


Fig. 1. Framework for CM resilience

2.1. Pre-Phase

This pre-phase is where the goal and scope of the project is determined and defined by the business. This phase entails all the standard project management activities required by the business undertaking the project to set a clear, appropriate and achievable outcome. The business must first ensure management and stakeholder commitment to the project and determine the ultimate goal and scope of the project. This must include a commitment to allocating appropriate resources and funding to the project. The business' individual circumstances will affect exactly what goal and scope is determined for the project e.g. a manufacturer making a single product for a single supplier could assess CM in 100% of its products for 100% of its customers as an achievable goal. However another company that manufacturers 1000's of different product lines for 1000's of different customers may decide, for example, that the most appropriate goal in their circumstance may be to assess CM in products that equate to, for instance, 1% or higher of their sales or revenue. Alternatively a business could select to assess CM in all products sold to key or selected customers.

Other parameters of scope must also be defined at this prophase such as geographic boundaries in the case of multiple sites or multinational corporations. Temporal scope must also be defined here so that there is a timeframe set for the project into which milestones and objectives can be set. The outcome from the pre-phase must include as a minimum

a top-level business commitment to the project including allocation of funding, personnel and any other required resources. The project must have clear leadership with roles, responsibilities and duties clearly defined, delegated and discharged. The overriding business objectives of the company undertaking the project will also set the scope of the project i.e. if a product line is soon to be discontinued then it may be left outside of the scope whilst another product or set of products that the company believes is important for its future goals may be focused on ahead of others. Whatever the final details decided it is at this pre-phase that project scope and various boundaries and parameters within the business must be clearly defined. The ultimate goal and intermediary objectives and milestones must be agreed and set with timescales for project completion and reporting. Once the pre-phase is complete the project may continue to Phase 1.

2.2. Phase 1

This phase of the framework is concerned with identifying CMs and any association they have with products throughout the value chain of a business. Initially the business must determine if it is a direct consumer of CM within its own processes. A business may buy one or more CMs as raw material that is used directly in the manufacturing of a product. The CM may actually become part of a product i.e. a neodymium for a magnet in a speaker or hard drive, or the CM may be utilised in the process but not contained in the product such as when used in polishing powders for glass and lenses or as a caustic cleaning agent. Regardless how they are used any CMs purchased directly by a business should be readily identified through their bill of materials. After the bill of materials has been checked for CMs the next step is to check it again for any components or other objects that are known to be likely to contain CMs. An external database of known components and uses of CMs should be utilised at this stage to enable identification of CM. Other data such as specifications for components and pre-fabricated parts is also to be utilised to enable CM identification at this phase.

Further primary information on CMs present upstream along the value chain can be obtained directly from suppliers to the business. Direct suppliers to the business may be able to provide good quality primary data on CM use however at every step one takes further away along the value chain it is likely to be harder to obtain good quality data. It is for this reason that good quality secondary data in the form of databases must be utilised to help determine possible CM use at each step in the value chain. It is essential to identify CM bilaterally both up and downstream along the value chain at this phase of the framework. Downstream identification will involve obtaining primary data from customers about how your products are used and into which markets and sectors they feed into. Again primary quantitative data should be obtained directly wherever possible but data bases of known uses and other qualitative data is used where primary data is absent. The position within the value chain where a business sits will determine its strategy for identifying downstream CMs. If it is selling completed products directly to the end

consumers then it will be straight forward to assess whether there is any CMs associated with downstream use. Likewise if a business has a single or relatively few customers then good primary data can be obtained on how exactly their product or products are utilised downstream and if there is any reliance or association with CM materials, products or processes. If a business is situated higher up the value chain then there is more potential for CM association simply due to the fact that there are more stages downstream along the value chain with more potential manufacturing routes and outcomes. This is where the scope and boundaries set in the pre-phase will determine how far, and to what level of detail the project investigates along the value chain. This may entail investigating only those products that meet a certain criteria of business strategy, percentage sales, revenue or association with particular customers as defined in the Pre-Phase.

All products falling within the defined scope must be investigated bilaterally using the best quality primary and secondary data available to identify all potential CM association before this phase is completed and Phase 2 may begin. If CM association is identified then the details of this would be examined and assessed during this phase. The likelihood of disruption due to the CM association must be assessed alongside the severity of impact to the product and business if the disruption did occur. This must be assessed within the context of the business and its' specific activities and circumstances. E.g. a business may have identified that it is reliant upon a small quantity of a CM in a single product that goes to a single customer, thus potentially posing a relatively small risk to the business, however after factoring in the business circumstances and business policy, it may be identified that this particular product in is a key element in the business strategy for future growth and so the potential risk for the business must be increased accordingly.

As discussed earlier this is an iterative process and the framework is not unidirectional therefore if during Phase 1 it becomes clear that the either the original scope or goal set are not achievable then the project must return to the pre-phase and continue to follow the framework. Likewise, if Phase 1 did not identify any CM throughout the value chain of a product then no further assessment or mitigation strategy would be required for that product and the next stage after interpretation could be to return to the pre-phase and broaden the scope or select the next category of products to be assessed. Once Phase 1 is complete with no further iterations required, a prioritized list of identified CMs and their associated business exposure is the required output before the business may progress to the next phase.

2.3. Phase 2

This phase utilizes the prioritized list of CMs that may impact the business as outputted from Phase 1 and assesses it against relevant external databases to determine the specific external risks of the CMs identified. The external databases will enable the company to understand the external likelihood of a supply disruption occurring for each CM identified as

significant for the business. It will enable information on the causes and different types of disruption events that may impact the supply of the specific CMs identified. The impacts of these disruption events to the CM supply will be identified at this phase including the most likely effects this will have on supply factors pertinent to the business. These supply factors will include such areas as the probable effect on total market availability and the potential for material substitution due to external factors (e.g. new materials being developed). Other factors that must be determined and considered at this phase include potential market price rises and fluctuations, the temporal effect across the supply chain including possible buffers i.e. how quickly a business will be affected by material supply disruption with regards to it's particular location in the value chain. This will include any known external factors such as large stockpiles of material that may slow down or conversely speed up the knock-on effect of supply disruption through the supply chain.

Understanding the temporal factors combined with availability and economic factors is essential to allow appropriate timescales to be considered for mitigation responses in the next phase. The required output from this phase is a complete assessment of all the external CM risk factors and their potential impact to the business. As with each phase of this framework, the Post-Phase interpretation must be conducted to assess whether another iteration or return to a previous phase is required. When no further iterations are required after interpretation, progression to the next phase can commence.

2.4. Phase 3

This phase utilises the information obtained and assessed in the previous phases to allow the assessment of the situation revealed and plan the appropriate business response with regards to potential mitigation strategies and associated resource allocation. E.g. through the previous phases a business may have identified a significant CM risk. The CM has been identified as having no viable substitutions that would not result in unacceptable loss of function and the CM is therefore essential for the manufacturing of the product. The likelihood of being unable to obtain a sufficient supply may have been assessed from external databases as being very high risk. This has been assessed as being very likely to lead to one of two scenarios. Either none, or insufficient amounts of the CM can be procured to meet the product quota, or procurement of the required volume is possible but at an increased price that may result in the product becoming unprofitable to manufacture based on internal financial information on product margins. Based on this information the business can select the most appropriate mitigation strategy for the specific problem.

In this particular example the business has the option to select many different existing risk management strategies and by following this framework it will be enabled to select the best option in each specific case. For instance, if in this example the product is soon to be discontinued and/or is

assessed to contribute a small revenue and has not been identified as being important for any particular customer or business objective then the company may assess that the risk to the business is so low that no mitigation strategy is required and if the CM does become unavailable, or, the price rises above a predetermined level then most appropriate strategy may be determined to discontinue the product at that point.

Alternatively all the factors in the example just given may be exactly the same except that it was determined that product goes to a key customer that makes up a significant slice of the business' revenue and/or there is a contract with a significant financial penalty so discontinuing the product may not be assessed as the most appropriate solution. If there is a contract to supply a known quantity of product then the best option may be to stockpile the CM now while it is available at a known price to ensure the order is discharged, margins are maintained and no penalties are incurred or customer relationships jeopardized. Alternatively there may be a contract to supply this product to a key customer on an ongoing basis so neither discontinuing production nor stockpiling the CM would be acceptable options. In this case the business may identify the need to ensure its own supply of CM and so could seek to adopt a material recovery plan by closing the loop either directly with the customer or further down the value chain.

To summarise, this phase utilises the data and assessments from the previous phases including the unique internal and external circumstance of every CM association identified and uses this information to select the most appropriate action in response through mitigation and resource allocation. The final stage of this phase is to collate and organise all the different responses identified to each CM association to enable the optimum implementation of the mitigation strategies in the project. If during this phase the business is unable to determine the optimum mitigation strategy due to lack of data or any other reason than the project must return to the relevant previous phase for another iteration and continue to follow the framework. When the business has been able to determine the optimum mitigation strategy for each CM and related product then this phase is completed and the project moves on to the Post-Phase.

2.5. Post-Phase

The post-phase runs in parallel with the pre-phase and phases 1, 2 and 3 and enables interpretation at each stage of the framework. This interpretation is essential at every phase as the framework works on the principle of iteration and it is through this post-phase interpretation that a business determines if it is in line with its original scope and goals or if iteration is required to bring it back into line. This post-phase also links back to the pre-phase, as during the course of the project it may become clear through interpretation that the original goal and scope need to be adjusted to allow effective or practical implementation and success of the project. The post-phase requires a review of all the primary and secondary sources of external and internal, qualitative and quantitative

data obtained each phase of the project to ensure that it is the best quality and most appropriate data available. Assessments of this data must be reviewed within the context of the current standard operating procedures and circumstances of the business and also against planned or expected future scenarios and business strategies. Only once this post-phase has been undertaken at every phase of the framework will the framework have been completed.

3. Case study

The following case study uses simulated data to exemplify the pre-phase and phase1 actions and outputs of the framework and how it is used to identify „critical“ materials, which could impact the resilience of the business, occurring both up and downstream in the company's supply chain. A manufacturer of precision power management systems, used predominantly in the wind turbine and electric vehicle industries, is concerned that it may be exposed to the risk of material shortages as defined in the EU's critical materials report 2010. The high performance to weight ratios of its products demands the use of advanced materials which may include, in part or whole, elements from this list. Furthermore many of their customer's products, in which their systems are subsequently used, are also highly sophisticated and could potentially be at risk from critical material, supply shortages. Whilst the company has taken steps to reduce risks associated with overdependence on individual supplier and customers, it had not previously considered the impacts that global supply shortages of these critical materials may have on its business.

The company decided that, for the initial review, the scope of would be limited to its own manufacturing operations and its primary (first tier) suppliers and customers. Also, only products within its advanced power systems range would be reviewed and the customer survey would be limited to the top 20% of customers that accounted for 80% of its revenues on this range. As it was unsure of which materials it was at risk from it decided to include all those on the EU's Critical Materials list. The aim of the review was to establish what CMs were being used where and to what extent disruption in their availability, within the whole value chain, could impact on the business. The review had the full commitment of the board and its importance had been communicated through the business by the CEO to ensure full and speedy co-operation.

Firstly an electronic search of the purchasing database and MRP system identified any materials, parts or components used in the manufacture of its advanced power range that contained the search terms listed in part or whole in their item description. The search terms were generated from a literature review of these CMs and included all variants of their full and abbreviated names in general use. This identifies two materials (1M and 1C) that were bought in as a material or component. At risk components were then checked against the manufacturer's specifications and a further component, 2C, was identified. These products containing 1M, 1C and 2C were then checked against sales data and the percentage value

of these products to the business was identified in terms of current and future revenue and profits.

In parallel with this purchasing and production review a customer review was undertaken by sales and marketing, identifying the key customers and establishing the likelihood of that customer's risk. Discussions were then held with key customers and a review of their manufacturing and sales operations, undertaken by them, identified CM's in direct or indirect use that could impact orders from this customer. This review highlighted that their customers' customers were also significant links in this value chain and so the company reviewed the pre-phase scope and adjusted it to include tier two customers.

This review identified that a CM (1S) was used in a customer's product, and that this product also used one of the company's non-CM containing products in its manufacture. This meant that sales of the company's product to this customer were dependent on them obtaining CMs for their own production. The products identified as being at risk were then prioritized based on the potential losses that could be incurred by the business from lost production and sales. This prioritized list forms the output of phase 1 and the input to Phase 2 where the frequency, likelihood and type of risk associated with the identified CMs are assessed.

4. Conclusions and Further Work

The need for sustainable manufacturing is widely accepted and the role of resilience, particularly regarding critical material supply, is a necessary component of achieving this.

Many companies are unaware of their exposure to CM supply issues and are therefore unlikely to develop mitigating strategies that leave them vulnerable to potential failure. The framework presented in this document provides a systematic approach to improving resilience of manufacturers to CM supply disruption, with reliable CM exposure identification as a key phase within this process.

The flexibility of the framework, using an iterative approach to developing complexity and understanding aids the efficient and cost effective use of resources that will increase the likelihood and success of its application.

Further work will now focus on supporting the implementation of the framework through the development of a computer aided tool and its validation through a formal case study.

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