CRITICALC Inception Report

DRAFT 11 October 2019

KAVA Reference (Number, Acronym, Full Title): EIT RM project number 18255, CRITICALC, CRITICAlity life long Learning Course

Name of the author/Responsible partner: Luis Tercero and Denis Stijepic / Fraunhofer ISI; Arnold Tukker / Benjamin Sprecher / Leiden University; Elmer Rietveld / TNO; Maria Ljunggren Söderman / Chalmers University of Technology
Version No: 1

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

Content

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

1. Introduction to CRITICALC

Raw materials criticality assessments are a merger of concept and data. Learners must understand both, and their relationship, in order to properly assess criticality.

The concept of "critical raw materials" has served to provide clear guidance to policy and to steer research funding for a more secure supply of raw materials for the European industry in the past decade. Following the seminal report "Minerals, Critical Minerals and the U.S. Economy" (NRC 2008), the Ad-hoc Working Group of defining Critical Raw Materials for the EU convened starting in 2009, leading to the publication of the report "Critical raw materials for the EU" (European Commission 2010) and contributing to a Communication on commodity markets and raw materials (European Commission 2011).

Since then, the List of Critical Raw Materials for the EU has been updated twice (European Commission 2014, 2017b) and there have been extensive efforts expended on understanding criticality and advancing the methodology for its determination at different levels (Buijs et al. 2012; Graedel et al. 2012; Graedel et al. 2015; Glöser et al. 2015; Helbig et al. 2016; McCullough and Nassar 2017; e.g., Blengini et al. 2017; Moss et al. 2013; US DoE 2011). This flurry of activity has led to a diversity of methodologies all trying to describe the same "phenomenon", which has not been unambiguously defined to-date. Although the methodology development activities continue on, it has become evident that dialogue and a common understanding are important in order to better use "criticality" for guiding policy and business decision. The EIT RawMaterials projects IRTC (International Round Table on Materials Criticality, www.irtc.info) and its business-oriented counterpart, IRTC-Business, are fostering this dialogue on an international stage.
At the same time, some course offerings have become available (see Chapter 2) targeted at both students and professionals, to introduce (potential) users to the concepts behind criticality assessments. However, data constitutes the bridge between an understanding of the concepts behind criticality and a useful criticality assessment. Therefore, there is a need to provide learners not only with conceptual knowledge but also to easy access to relevant data. CRITICALC aims to combine these two elements into a modular, flexible, blended learning course offering. The elements and ambition of CRITICALC are shown in Figure 1. Learning objectives are to understand what makes materials critical, how to assess criticality, to analyse economic and other implications of criticality at company, sector and country level, and to develop strategies to reduce criticality risks. TNO has a criticality assessment tool available developed for Dutch SMEs

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

and OEMs ('grondstofscanner' or 'raw materials scanner'[1]). Contacts of the project team with other organisations in Europe, such as the Deutsche Rohstoffagentur (DERA), show the need for similar and more expanded tools for Europe as a whole. For use in the course, the Dutch tool will be translated and expanded for use in an international context. Learning materials will be criticality literature, exercises (a.o. with the tool), and case studies or teamwork in small projects. Classes will be taped. All material will be electronically available so that ultimately a 'blended learning' package is produced. The course will be tested during the project with over 250 students, and the lifelong learning version will be offered commercially after the end of the project.

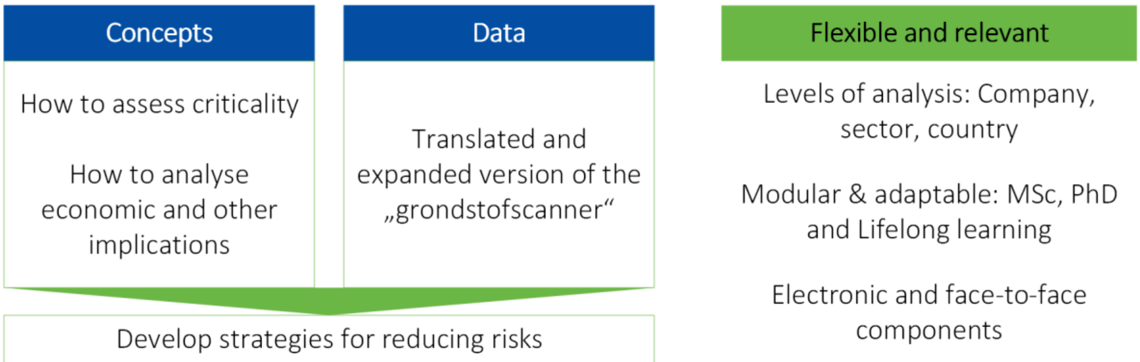

Figure 1: Learning objectives, data basis and modalities of CRITICALC courses.

2. Available course offerings

The concept of raw materials criticality is relevant at all stages of the raw material cycle and for different aspects of raw materials markets. Therefore, the topic of critical raw materials is touched upon in varied course offerings ranging from mining to material science (especially for substitution) to recycling. In this chapter, we offer an overview of tools and courses already available internationally on criticality.

[1] https://acc.grondstoffenscanner.nl/#/. The Grondstofscanner evaluated the 5000 product categories in the HS trade classification system and analysed per type of product if critical materials are likely to be present. From there, by selecting products relevant for specific companies (OEMs, other) one can see which materials form a risk and why.

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

2.1. University courses

Many universities offer or have offered traditional/presence lectures, courses or study programs on, e.g., industrial ecology, engineering materials and sustainability, sustainable materials management or sustainable development for (master) students, which cover the topic of raw material criticality to some extent. Examples are the Universities of Augsburg , Surrey, Zurich (ETHZ) and Basel (University of Augsburg 2019; University of Surrey 2019; ETH Zürich 2015; University of Basel 2017).

Critical Materials Institute (CMI) offers an extensive overview of educational opportunities relevant for critical material studies (CMI 2019a). The educational offers range from short courses and webinars to lectures and graduate research programs offered by CMI's partner institutions, e.g., Colorado School of Mines and Iowa State University. They target different audiences (including industry, students and researchers). However, CMI's education package cannot be regarded as a clearly structured program with immediate focus on material criticality; rather, it is a broad overview of educational opportunities covering many different topics that are (indirectly) relevant for material criticality studies (CMI 2019f, 2019d, 2016, 2019e, 2019g, 2019b, 2019c). The American Geosciences Institute (AGI) offers webinars on raw material criticality (AGI 2018b, 2016, 2014, 2018a). Simply speaking, these webinars are video lectures given by different experts via the AGI homepage or another provider (e.g., YouTube). For some of these lectures, accompanying slides are provided as PDF files.

We further cross-checked via an e-mail inquiry with a number of key universities known to work in the field of Industrial Ecology and/or material flow analysis and resources if they have any dedicated classes on criticality assessment. We contacted for this senior staff working in the resources field at:

- Yale University, MIT, the University of California in Santa Barbara (all US)
- NTNU (Norway)
- KTH, (Sweden)
- the Institute of Urban Ecology of the Chinese Academy of Sciences (Xiamen, China)
- the National Institute of Environmental Studies (Tsukuba, Japan)
- the University of Sydney and the University of New South Wales (both Australia).

In addition, we further obviously cross-checked as well the MSc courses on Industrial Ecology provided by project partners Chalmers University of Technology and Leiden University. From the

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

responses we learned that most of these universities offer relatively extended courses (e.g. 7.5 ECTS) or even full MSc programs (60-120 ECTS)[2] that cover for instance Life cycle assessment, Material flow analysis, Input Output analysis, and other approaches to assess flows of products and materials in the economy at different levels of scale. Some of these courses do address the issue of criticality, and methods to assess criticality. But invariably, the topic of criticality and supply chain security in such courses is addressed at best in a day or 2 of the classes, often just few hours. Several universities also have developed Massive Open Online Courses (MOOCs) that address the issues above, but also here the part dedicated to criticality assessment usually is just a small part[3].

There are further criticality courses targeting primarily business administrators or supply chain managers. Like the university courses above, they represent a relatively general view on criticality: they understand criticality as the risk of supply default (in the sense of quality or delivery default) from the viewpoint of a corporation/enterprise that is dependent on its supply chain. Thus, these courses on 'criticality' do not deal specifically with the natural, physical or geopolitical aspects of criticality of raw materials but with the criticality of intermediate inputs with a focus on the aspects of business administration, supply chain management and corporate process control (PiLog Group 2018; CfPA 2018, 2019; ISM 2019). This 'supply chain criticality view' can be useful for the CRITICALC project as we also aim to cover the implications of criticality at company level.

2.2. EIT RawMaterials

Master Programs

All EIT-labelled master programs deal with issues that are more or less directly relevant for raw material criticality studies (EIT RawMaterials 2019b). In the following, we list the master programs and teaching units that explicitly mention raw material criticality in their (publicly accessible) announcements or syllabuses.

---

[2] ECTS stands for the European Credit Transfer System which measures study credits of a course in a standardized way (time spent on self-study, preparations and other self-work, contact hours, exams). A full time study year equals 60 ECTS.

[3] An illustration is the MOOC A Circular Economy of Metals: Towards a Sustainable Societal Metabolism thought by staff of Leiden University, see: https://www.mooc-list.com/course/circular-economy-metals-towards-sustainable-societal-metabolism-coursera (accessed 15 August 2019), developed with support of the EIT KIC RM

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

- The master program Advanced Materials: Innovative Recycling 'AMIR' includes the teaching unit TU1-4: Sustainability and Life Cycle Assessment of Materials, which covers criticality assessment methods (AMIR 2019).
- A key aspect of the master program Advanced Materials for Innovation and Sustainability 'AMIS' is the substitution of critical materials in products (AMIS 2019).
- The EMerald Master Programme in Resource Engineering (EMerald 2019) includes the course Solid Waste and By Products Processing, which contains a section on emerging technologies and demand for critical raw materials (Liège Université 2019).
- The master program Sustainable and Innovative Natural Resources Management 'SINReM' includes the course Critical Metals & Minerals (SINReM 2019).
- The master program Sustainable Materials (SUMA 2019) includes the course Recycling and Sustainable Materials, which discusses criticality as a basic concept (Università di Trento 2016).

PhD Programs

EIT-labelled PhD programs, in particular IDS-FunMat-Inno and IDS-FunMat-Inno-2 (are planned to) cover the topic of recycling and substitution of critical raw materials (EIT RawMaterials 2019c; IDS-FunMat 2019; EIT RawMaterials 2019e).

Face-to-face (life-long learning) courses

Currently offered face-to-face courses cover different aspects of raw material criticality.

- The introductory section of the course Corporate Social Responsibility – A Life-Cycle Assessment from Prospect to Closure deals with criticality as a societal trend/challenge (EIT RawMaterials 2019a).
- Similarly, the introductory section of the course Exploration, (E)Valuation and Reporting of Raw Material Deposits deals with criticality as a trend (EIT RawMaterials 2019d).
- The program of the RawMatCop Academy 2019 includes introductory aspects of raw material criticality and a case study on critical raw materials exploration in tailings (EIT RawMaterials 2019g).
- A part of the course Reporting in the Mineral Industry - Resources & Reserves, Asset valuation, Sustainability & Social Responsibility deals with reporting to the society on critical raw materials (EIT RawMaterials 2019i).

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

Wider Society Learning

Several (planned) learning projects of EIT RawMaterials target the wider society. In particular,

- the Raw Matters Ambassadors at Schools project includes toolkits (experiments) for presentation at schools dealing with substitution of critical materials (RM@Schools 2019) and
- REFER: Raw Engagement for Electronics Repair seeks to "raise the awareness of critical raw materials in wider society through electronics repair events" (EIT RawMaterials 2019h).

The SusCritMat project (Sustainable Management of Critical Raw Materials)

Several educational opportunities are provided/funded by EIT RawMaterials via the SusCritMat project (SusCritMat 2019a):

- SusCritMat has developed video learning contents in the form of a Small Private Online Course (SPOC). This covers the following critical-materials related topics among others (SusCritMat 2019d):
    - introductory discussions of critical raw materials (e.g., definition, issues concerning extraction and use and historical development of the topic),
    - supply risk factors in criticality assessment and
    - demand and supply scenarios of critical raw materials.
- The SusCritMat schools (summer, autumn, winter schools) cover(ed) various key raw-material criticality topics, among others
    - introduction to criticality and fundamental concepts,
    - assessment of information to perform economic importance and supply risk calculations,
    - criticality assessment and analysis of criticality and
    - solutions to criticality problems (e.g., responsible sourcing).

  For a detailed overview, see the programs of the SusCritMat Winter School 2018 (SusCritMat 2018a) and SusCritMat Summer School 2019 (SusCritMat 2019c).

- The SusCritMat short courses cover special aspects of raw materials criticality assessment. In particular, the SusCritMat Short Course 2018 focuses on the criticality assessment of cobalt (SusCritMat 2018b), and the SusCritMat Short Course 2019 deals

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

with the criticality assessment of cobalt and lithium in the context of batteries and electro mobility (SusCritMat 2019b).

This material is already being used or adapted for use in other contexts. For instance, Leiden University will use the SPOC video learning content in a 7.5 ECTS course on a Circular Economy and Governance part of a new MSc on Governance of Sustainability.

Online Courses

Several online courses and webinars related to critical raw materials are funded by EIT (RawMaterials), e.g.,

- the TU Delft's online course Waste Management and Critical Raw Materials focusing on recycling of critical raw materials (TU Delft 2019),
- the RoMa webinar The Added Value For The European Economy of Recycling of Secondary Critical Raw Material Within Europe, which provides an introduction to raw materials criticality and related circular economy aspects (EIT RawMaterials 2018), and
- the RoMa webinar Metal Recovery: An Efficient Example of Integrated Leading Technologies for Cobalt Recovery, which provides an introduction to raw materials criticality and related circular economy aspects based on a cobalt case study (EIT RawMaterials 2019f).
- a MOOC that is developed as a follow-up of SusCritMat, on analysis and management of Critical Raw Materials.

3. Available criticality assessment tools

3.1. Studies that have resulted in assessment methodologies

In recent decades, the policy relevance of raw material supply has emerged and has resulted in a series of policy documents. A number of publications followed assessing the criticality of raw materials. Criticality can be considered the potential risk of supply disruptions and the resulting impact on the economy or on the implementation of certain policy goal (such as, for example, the implementation of alternative sources of energy). An early review of these criticality analyses was published by Erdmann and Graedel (2011). The EIT RawMaterials project IRTC is preparing an updated overview of criticality studies and furthering this discussion on international fora (http://irtc.info).

These studies show that criticality can be about security of supply (for a company, a sector or a region) but also about potential effect on competitiveness, R&D decisions and reputation of an individual company or other organisations. Price levels of raw materials can directly affect the "bottom-line" of a company or public budgets, but prices can also influence strategic decisions. In terms of reputation, companies and public authorities are becoming ever more sensitive to the influence of pressure groups and the environmental movement as a consequence of the rapid spread of information via social media. This in turn has a direct effect on market value of products or the political acceptance of public expenditures. Two examples of raw material criticality indicators shown in Table 3.1 and Figure 3.1

Table 3.1: Criticality indicators from Graedel et al. (2012)

	Components	Indicator
Supply risk	Geological, technological, economic	Exhaustion time (Reserves / Production)
		Accompanying metal fraction
	Social aspects	Human development index
	Geopolitics	WGI
		Global supply concentration
Vulnerability to supply constraints	Interest	Percentage of income that is affected
		Ability to pass on cost increases
		Importance for the company strategy
	Substitutability (chemistry)	Performance replacement products
		Availability replacement products
		Environmental Impact Ratio
		Price Ratio
	innovation capacity	Business Innovation

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

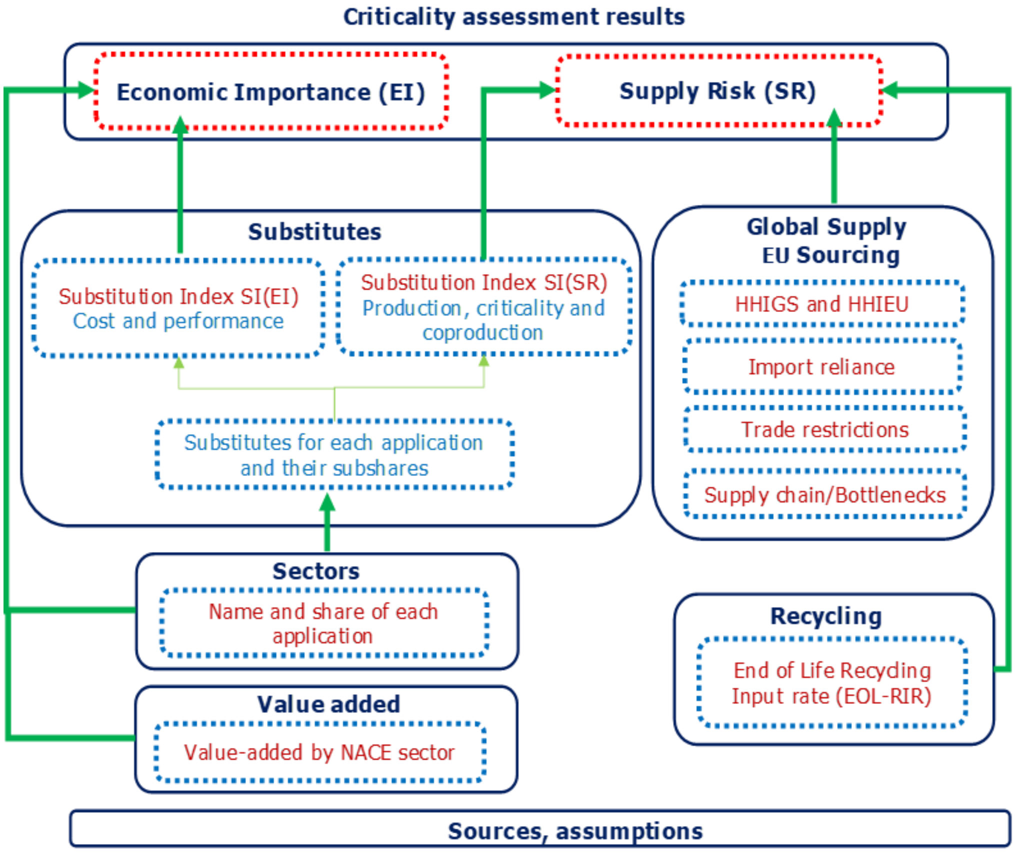

Figure 3.1: Criticality indicators from European Commission (2017a)

Scholarly work has recently progressed critical raw material assessment beyond the usual empirical criticality assessment shown in Table 3.2. A first possible relevant work is delivered by Bensch et al. (2015). This work develops a conceptual decision and Information Systems integration model for the assessment of products based on their raw material composition and implements this model as a software prototype. The fact that this work uses mostly criticality indicators available in the resource scanner makes it less relevant for the extension of the analytical framework beyond the indicators shown in Table 3.2. However, the way that data is managed in the tool that is part of this paper might be interesting in later stages of the Criticalc project.

An academic contribution that truly opens a new paradigm in assessing criticality is offered by Sprecher (2016). It discusses an socio-technological system that assesses the production-consumption system, the supply chain and resources and the individual companies. It offers an

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

analytical framework based on resilience of a system, depending on factors that either allow it to directly maintain function under disturbance, to rapidly recover from a disruption, or to switch between alternative systems that can provide the same service. Resilience is defined in this work as:

- Resistance; the system maintains it function, i.e. it is able to tolerate various types of disturbances without experiencing unacceptable loss of function.
- Rapidity; the system is able to rapidly recover so that it meets its goals again within a short period following the disturbance.
- Flexibility; the system is capable of meeting supply needs under a disturbance by switching between different (alternative) subsystems.

It is suggested that the levels of the socio-technological system and resilience are introduced in the criticality assessment of the CRITICALC project, either qualitative or quantitative. Even indicative rankings and characterisations of the resilience elements can add depth to the quantitative assessment of indicators (for instance those in the GSS). Moreover, describing resilience and systemic risks can refer to relevant work that deepens the understanding of criticality. An example how this relevant work can be an add-on to criticality assessment is to create System Dynamic diagrams for specific products or raw materials, as is done in Sprecher (2016)

3.2. Available tools and data portals

While the calculations for criticality assessments are certainly done on a computer using purpose-made tools, these tools remain outside the public realm. The existence of the criticality indicator frameworks inspired some organisations to create web-based data portals and tools to allow stakeholders to assess raw material criticality for themselves. Here, we briefly present three such tools/portals that enable users to gain insights into raw materials criticality. There are of course many more on-line tools that help to assess environmental footprints or to perform LCAs, but we limit ourselves here to tools that can help in criticality assessments.

The first example of a data portal is ROSYS of the German Raw Materials Agency (DERA 2019). This portal provides high-quality information about the production and use of minerals and metals, the trade dependence of Germany, the relevance for the energy transition and price information. A more through description of ROSYS can be found online, the main properties of this data portal will be shown in Table 3.2. A similar web-portal providing information is the

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

mineral site of the French ministry of Economic Affairs (BRGM 2012-2019), but it is only available in French which impedes a use for non-French speaking users.

Another example of a web-based raw material resource is the Raw Material Intelligence System of the Joint Research Center of the European Commission (JRC 2019). It has arguably the best visual representation of the raw material supply chains and systemic aspects of criticality, not to mention the excellent knowledge base that feeds the system continuously updated information. The system can however only be queried on one specific topic at the time (recycling, countries of origin, supply chain issues). A more through description of RMIS can be found online. The main properties of the tool will be shown in Table 3.2.

The third example is a raw material criticality assessment tool, the "The 'Grondstofscanner" (GSS) or Resource Scanner. This tool was created by (TNO, EY, HCSS, Leiden University 2017). It not only provides information about criticality, it also enables users to create their custom made assessment. It is the only existing tool that is specifically created with the aim of providing a user-specific criticality assessment, where for instance ROSYS and the RMIS are mainly aimed at providing information. The Resource Scanner evaluates the dependence of users (executives, policy makers, R&D, procurement professionals) on raw materials based on their selection of product groups, signifying the custom-made character of the tool. The tool can calculate the environmental, social and reputational impacts of extraction and production (supply, price of minerals and metals used), as well as the risk associated with volatile supplies. The tool includes fact sheets of products and a list of raw materials needed (e.g. batteries) and fact sheets for raw materials (e.g. iron, silver)" (EREK 2019). There are two country specific elements to the data in the Resource Scanner that require a modest follow up of user outside the Netherlands. They need to check international trade flows themselves to ascertain trade of specific product groups for their region of interest. Apart from that, they can only see a global WGI and HDI score related to countries, not a weighed WGI and HDI score for their selection of products, as these latter scores are tailored to the Netherlands trade relations with the Rest of the World (and not the trade relations between countries within the Rest of the World).

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

Table 3.2: Comparison functionality between online criticality tools

	ROSYS	RMIS	GSS
Nation states where metals are extracted i.e. produced in raw form	Yes	Yes	Yes
Time series of world production	Yes	No	No
Nation states where metals are refined i.e. produced in intermediate form	Yes	Only trough traded product groups/commodities	Only trough traded product groups/commodities
Data on production of energy carrying materials	Yes	No	No
International trade by raw material	Only for Germany	For EU, not Member States	Only for the Netherlands
International trade by origin & destination	Only for Germany	For EU, not Member States	Only for the Netherlands
Price information	Timeseries	Timeseries	One year only
Price volatility per raw material	No	No	Yes
Relevant public policy documents	No	Yes	No
Qualitative background information on raw materials	Basic	Extensive	Basic
Quantified description of material system, including entire value chain, stocks and waste flows	No	For 20 raw materials on the spatial level of the EU	No
Environmental impacts per raw materials	No	Yes	Yes

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

	ROSYS	RMIS	GSS
Supply chain viewer based on NACE2 sectors	No	Yes	No
Link between raw materials and HS/CN product groups	No	No	Yes
Companionality information	No	Yes	Yes
Weighed HDI, EPI and WGI scores based on product group selection	No	No	Yes
Presence of substances relevant for REACH	No	No	Yes

As a final example, the "Sustainable Development Edition" offered by Granta Design (2019c) contains multimedia tools on sustainability covering among others critical materials (Granta Design 2014, p. 10, 2019a). In general, Granta Design provides different multimedia education packages (on sustainability), where criticality is mentioned or discussed to some/lesser extent (Granta Design 2019d, 2019e). This means that the information of Granta (Granta Design 2019b) could not only provide criticality assessment, it could also serve as a resource in assembling the teaching materials in WP2.

3.3. Conclusion for implementation plan

Given the access to the underlying data, the consortium's deep knowledge of the calculations performed in the tool and the custom-made character, we decide to take the Resource Scanner (GSS) as a starting point for the supporting tool in the CRITICALC project.

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

4. Implementation plan

4.1. Objectives of Criticalc

CRITICALC aims to develop a modular course on criticality assessment of materials in supply chains that can be tailored for use in MSc, PhD and lifelong learning education programs.

Despite its importance, in particular for policy and strategic business decisions, the concept of raw materials criticality is only briefly touched upon in higher education to date (see above). Here it is mostly a motivation for recycling or substitution, but the concepts themselves are rarely transmitted comprehensively. A notable exception is the SusCritMat project, which focuses on raw materials criticality but only offers one-week "Schools" and one-day narrowly-focused "Short Courses" but neither the semester-long courses required for universities nor the compact courses apt for professionals. CRITICALC will create a modular set of blended learning materials that is usable for these two settings, supported by an on-line assessment tool. Delivering the content, tools and courses is structured into three Work Packages in CRITICALC. These are:

- WP 2: Assembling of blended learning teaching materials
- WP3: Analytical software
- WP4: Live testing of courses

In the next sections, we will discuss the approach to each WP based on the initial inventory of education materials and assessment methods.

4.2. Work Package 2: Assembling teaching materials

The objective of this WP is to make blended learning materials suitable for life-long learning, which will allow course participants to develop their own criticality assessment and improvement scenarios using the software to be assembled/developed in WP3. The scenarios can be at micro-level (e.g. designers, business developers) or meso and macro level (strategic planners,

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

government agencies). This will result in educational courses that due to a modular structure can be implemented at different levels for different target groups. We envisage to set up the educational package in a modular form. This allows to serve various target groups with different variations of the educational package, also enabling learners to follow the course at their own pace and following only modules relevant for them:

1. Undergraduate/MSc level. Here the package will be suitable for a base or elective course of up to 5 ECTS (3-4 weeks full time). Such a course could be useful for engineering programs in e.g. Geosciences, Geoengineering and Mining, Materials Science and Materials Technology; science programs in e.g. Economics & Supply chain management and Environmental management/Industrial Ecology, etc.
2. PhD level courses, e.g. in the form of a Summer school of 1 week, focused at PhDs for which supply chain risks from a technical, environmental or economic perspective are relevant. Around 2 ECTS.
3. Lifelong learning courses, focused on supply chain managers and similar in companies. Such courses typically should be concentrated in 2 days at maximum for the physical course.

For this purpose, we envisage a modular course design that allows using the same course materials for different target groups. At MSc level, we envisage full week course with exercises and expanded with a project assignment, that can count for a 4 week/5 ECTS course. But without the project assignment, the course can serve as a 1 week introduction to criticality assessments, as a shorter MSc course or a course for PhD students. In the lifelong learning variant, we will condense the teaching and exercises to 2 days, what usually is the maximum time that professionals spend on external courses.

Table 4.1: Modular course structure

Content	**MSc: 4 weeks**	**PhD: 1 week**	**Lifelong: 2 days**
Criticality backgrounds	Day 1	Day 1	Day 1
Tool/platform	Day 2	Day 2	
Micro-Application (theory)	Day 3	Day 3	Day 2
Macro-Application (theory)	Day 4	Day 4	
Case studies	Day 5	Day 5	
Additional exercises	YES	n/a	n/a
Project assignment.	YES	n/a	n/a
ECTS	5	2	1

From chapter 2 it becomes clear that the SusCritMat project already has developed a wealth of teaching materials for different applications. Conversely, we found that most other educational programs touching upon criticality do so in a relatively short time and as a part of a general

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

course on material flow analysis, LCA, or similar. Table 2 identifies the key tasks and course elements mentioned in the project proposal that have to be developed in WP2, and the approach we currently feel is the best way of developing them.

Table 4.2: Tasks and course elements to be developed in WP2 and envisaged approach

Key tasks and course elements to be developed	Approach to the task and materials to be developed or used
1. Development of the learning goals of each learner group, for instance: a. what makes materials critical, b. how to assess criticality, c. how to analyse economic and other implications of criticality at company, sector and country level, d. how to develop strategies to reduce criticality risks.	Develop a concise outline of these learning goals in 1-2 A4. Discuss and finalise after the inception workshop
2. Development of written materials (Background report and reading materials, Slides)	Inventory course materials from the sources identified in chapter 2 of the inception report. Inventory reports or scientific paper describing the most relevant criticality assessment methods (e.g. the EU method, the US DoE approach, and methods proposed by e.g. Yale University and the CRI). Develop an own manual of the criticality assessment tool that this project will offer. Make a reading list with an appropriate length for the one week MSc and PhD courses and the 2 day life long learning course. Develop, in part based on usable materials from other courses identified in chapter 2 of this inception report, presentations that discuss: • Criticality background • Tool/platform • Micro-Application (theory) • Macro-Application (theory)
3. Developing of around 10-15 exercises which will measure the knowledge gained by the learners, also demonstrating how the learning objectives were achieved	Develop exercises, in part based on material inventoried from existing courses identified in chapter 2 of this report. The exercises will combine the criticality methods discussed under 2), the tool/platform, or readily provided basic information on e.g. material sources, economic relevance of sectors, so that students can assess themselves: • what makes materials critical, • how to assess criticality, • how to analyse economic and other implications of criticality at company, sector and country level, • how to develop strategies to reduce criticality risks.
4. Developing video movies / youtube clips reflecting key stages in the course, taped from classes given during the test courses in WP4 and taped by a professional. These will be developed using best practices on video length etc. and be hosted on youtube or a course website of UL-	Investigate is the SPOC developed in SusCritMat and/or the MOOC on Critical materials currently developed in the EIT RM is to be preferred above taped classes in the current project. Otherwise, arrange for making good quality own video movies of test courses in WP4

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

CML or Chalmers.	

4.3. Work Package 3: Analytical software

The goal of this WP is to deliver a web platform in which learners can perform the assignments relevant for the course. The platform in essence allows for assessing the criticality of materials and individual components used in supply chains at company, sector and country/EU levels creating scenarios for sustainability improvements with all aspects of (raw) materials management and analysing the improvements including trade-offs from micro to macro level. The main tasks in this WP are listed in Table 4.3

Table 4.3: Tasks and course elements to be developed in WP3 and envisaged approach

Key tasks within WP3	General approach to the task and deliverables
Create web-platform for the teaching materials	Following the example of other KIC EIT Raw Material projects, a platform can be created with easy download opportunities and facilitating interaction between users. The deliverable is an operating and well-maintained website.
Establish user needs	The user needs will be explored by considering state-of-the-art criticality assessment papers, initial user feedback from the first phases of WP4 and the teaching materials assembled in WP2. The deliverable are technical requirements for a next version of the GSS or similar self-assessment tool.
Creating independent software	Previous attempts show that the GSS can be emulated i.e. mimicked by code that is written from scratch. The deliverable of this task is a program that is available on the web-based platform and provides additional functionality compared to the existing GSS.

Create web-platform for the teaching materials

The KIC EIT Raw Materials projects Ramascene (https://www.ramascene.eu/) and Circumat (https://cml.liacs.nl/cmat/) delivered results on a web-based platform. A similar platform will be created for the CRITICALC project, linking and gathering all the relevant research resources.

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

Search options based on key words and topical sorting will enable to search the teaching materials effectively.

Establish user needs

As stated in §3.3, the software tool intended to be further developed in this WP follows the approach of the Resource Scanner (abbreviated GSS; developed by TNO, EY, HCSS, Leiden University 2017). Using the Harmonized System (HS) product classification that classifies some 5000 in the UN COMTRADE database for foreign trade. Other relevant previous work is available to enrich the GSS, like the H2020 SCRREEN, MICA, PANORAMA and PROSUM projects. These deliver the information to investigate which products will be identified and what they contain in terms of critical raw materials. For each product hence and indication of composition becomes available. The minimum variant to be used in the readily available, an English version of the GSS that allows users to assess one or more of the 2400 product groups in the international context.

User needs will be initially identified by allowing users to test the GSS in focused sessions, where they are requested to share both their expectations before use and experiences after use. Deploying the GSS should provide an indication of criticality related to primary resource content for each product, for the region and sector of interest. By using the background databases of the projects mentioned above, the GSS already provides a useful tool to assess potential criticality problems of components.

Further user needs can be formulated based on recent scientific work and the teaching materials being provided to users by WP2.

Creating independent software

Where we start using the GSS, the ambition of this project is to provide an open source script that emulates the GSS. This software can subsequently be used by this consortium (and anyone for that matter) that wants to translate the user needs as established in the other task to an improved self-assessment tool .

An example of an identified user need, and the translation of this need to self-created software, would be the analysis of a supply chain. It would be a major achievement if the software allows user to use specific supply chain information that users have as input. This data would be based on company specific knowledge. It is normally very difficult to create a meaningful image of a supply-chain based on public data alone.

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

From 3.2, we learned that most GSS content is relevant for the whole globe. There is also content that is tailored to the Netherlands, that needs to be made global in the independent software. But the self-created software can go beyond the status-quo. In doing so, there are two categories of content in the independent software that could be delivered compared to the existing GSS: expected must-haves and nice to haves. It is almost certain that a GSS will be delivered that includes trade data for all member states. Moreover, the weighed WGI and HDI for every MS specifically can be calculate din relatively short time. Information about companies, ownership, substitution, labour conditions and environmental impact will be added, data permitting. Illustrating supply chain based on typical product groups, as mentioned above, is information that is likely to be delivered in a visually attractive manner. Geographic information will be presented using open source GIS software.

The table below shows the content that is part of the GSS (global and Netherlands specific) and the possible new content (expected must-haves and nice-to-haves).

Table 4.4: Overview of content in the independent software that is, should be or could be available

Existing GSS, global	Existing GSS, content tailored to Netherlands that	Expected must-haves	Nice-to-haves
Global production i.e. extraction of materials, including country of extraction			
Companionality materials			
Price volatility materials			
Impose trade barriers HS/Cn 6 digit product group as listed by OECD			
WGI, EPI, HDI scores per country			
Global recycling rates			
Environmental impacts per kg of metals			
	WGI and HDI scores		

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

Existing GSS, global	Existing GSS, content tailored to Netherlands that	Expected must-haves	Nice-to-haves
	for import to the Netherlands		
	Import and Export of HS/CN 6-digit product groups (around 2400 groups) to the Netherlands		
		Country specific Environmental impacts per kg of metals	
		Country specific HDI per metal, describing labour conditions	
			Companies & ownership of companies
			Substitution,
			Illustrating supply chain based on typical product groups
			Qualitative assessments or quantitative, official data driven scores: Socio-technical system, 3 aspects
			Qualitative text: Complex Adaptive Systems framework
			Qualitative assessment or quantitative/illustrative

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

Existing GSS, global	Existing GSS, content tailored to Netherlands that	Expected must-haves	Nice-to-haves
			content: Resilience system properties of product groups or materials

4.4. Work Package 4: Live testing

MSc course: we will use the MSc on Industrial Ecology at UL-CML (80 students) and at Chalmers (40 students) to give a short version of the course in obliged method classes of the MSc, twice and once, respectively, leading to at least 200 involved students. We further will use the 4-week version of the course as elective in the MSc of UL-CML.

PhD course: this course will be open for any PhD student, but we aim to offer it as a potential elective to existing PhDs schools in relevant fields such as environmental studies, energy, materials science and geosciences. In addition to such already identified schools, we will approach a selection of ongoing Innovative Training Networks for doctoral training under the EC Marie Skłodowska-Curie Actions Programme. For this level, one live test will be conducted towards the end of the project so that the course builds on several previous tests and revisions of MSc and Lifelong learning modules. A summer school is envisioned, but the timing is to be aligned with the PhD schools in question.

Lifelong learning course: this course is planned to be offered once in Sweden with support from several platforms specifically aiming for promoting transdisciplinary collaboration and education as well as critical raw materials. The Swedish Lifecycle Center (SLC) is a Swedish collaboration platform for academia, industry, research institutes & government agencies which regularly offers seminars and courses for its members. Chalmers Professional Education is a subsidiary of Chalmers which offers commissioned courses for industry and authorities in numerous areas. The global rare earth industry association (REIA) focuses on development of an integrated, de-risked and sustainable value chain for various rare earth material product, including capacity building for REE practitioners. The Critical Raw Materials Alliance (CRM Alliance), founded by industry, advocates the importance of critical raw materials for the European economy and promotes a

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

strong European CRM policy. By using such existing platforms, we will have a large reach to professionals in various member states and relevant industrial sectors and governmental bodies.

The courses build on the principle of constructive alignment so that teaching and learning activities and assessment tasks directly address the intended learning outcomes. All live tests will thus include internal reviews of intended learning outcomes and activities to ensure that constructive alignment is achieved. Furthermore, participants' opinions on content and format will be gathered through structured and comprehensive evaluations. The evaluations will provide feedback to both WP2 and WP3.

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

Table 4.5 Time plan for live tests

Course	M1-6	M7-12	M13-18	M19-24	M25-30
MSc Leiden Chalmers				Leiden Chalmers	
PhD				Summer school	
Longlife learning			Sweden		

5. Initial plans for financial sustainability

As already indicated in the project proposal, sustainability of the project results (both financial as otherwise) can be guaranteed as follows.

- First, UL-CML and Chalmers run MSc programs in the field of Industrial Ecology and the Circular Economy in which the course will be used.
- Second, we will continue to offer the course during PhD schools.
- Finally, the course will be offered for a fee to professionals (e.g. 2 schools per year, up to 20-25 participants, 2000-3000 Euro fee).

The course can be given remotely or on location, in pre-organized sessions or on-demand. The costs for 1-2 teachers including preparation are 1-2 person months or 10-20.000 Euro. Another 600-1000 Euro per participant may be needed for lodging and food in case of an on-site event, leading to an estimated expenses of 40-50.000 Euro in total for 2 courses.

In the two years that the project still runs, the project participants have to agree on which partners will take responsibility for the course. At this stage, it seems most logical that UL-CML and Chalmers, for whom unlike FhG and TNO teaching is a core activity, will be the hosts of the course. They have to advertise the course, make teaching facilities and teachers available, and have a registration and payment system operational. Details will be elaborated as part of the management WP in the remaining duration of the project. By Month 20 (Fall 2020) this spin-off strategy should be operationalised.

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

6. Risks and countermeasures

The combined experience of the consortium members underpins the feasibility of the project. Nevertheless, the consortium is aware of a number of risks affecting the project. Foremost among them are:

- Mismatch between course offering and needs of students and practitioners. This risk is addressed by an open inception workshop, in which the concept of CRITICALC and the approach are presented to interested stakeholder at a relevant, multidisciplinary conference (World Resources Forum).
- Course materials are not adequate. The consortium has both the educational expertise (Leiden und Chalmers Universities) and the required deep knowledge of criticality assessments (TNO was part of the consortium which helped produced the EU List of Critical Raw Materials in 2017; Fraunhofer ISI supported the initial methodological developments and the preparation of the EU List of Critical Raw Materials published 2010 and 2014). This also brings a degree of redundancy into the consortium should there be any personnel bottlenecks.
- Software tool is not ready on time or is inadequate. By building on a functioning tool co-developed under TNO lead, the consortium has a head-start in the software development and builds upon a proven basis. The live testing will be able to proceed even in the (highly unlikely) worst-case scenario where no original software can be developed within the project and modular course delivered by CRITICALC relies on the existing Resource Scanner.

7. References

AGI (2014): 2014 Critical Issues Forum: America's Increasing Reliance on Natural Gas: Benefits and Risks of a Methane Economy. American Geosciences Institute (AGI). Available online at https://www.americangeosciences.org/webinars/critical-issues-forum-2014.

AGI (2016): Underpinning Innovation: The Science and Supply of America's Critical Minerals and Materials. American Geosciences Institute (AGI). Available online at https://www.americangeosciences.org/webinars/critical-minerals-materials.

AGI (2018a): Playlist: Policy & Critical Issues. Video No. 18ff. American Geosciences Institute (AGI). Available online at https://www.youtube.com/watch?v=FufLx3aRRX0&list=PLTBBygdCOWWdcLZcFKwQrbU84IUTt4sE1&index=18.

AGI (2018b): Tracking the Global Supply of Critical Materials. American Geosciences Institute (AGI). Available online at https://www.americangeosciences.org/webinars/tracking-global-supply-critical-materials.

AMIR (2019): AMIR Master - Overall Program Structure - Detailed Contents - 1st Semester. Advanced Materials Innovative Recycling (AMIR) Master Program by Université de Bordeau, Technische Universität Darmstadt, Universidad Politécnica de Madrid, Liège Université, Miskolci Egyetem and Faculdade de Ciências e Tecnologia (Universidade Nova de Lisboa). Available online at https://www.amir-master.com/first-year-university-of-bordeaux.

AMIS (2019): AMIS Master - Your Impact. Master's Program in Advanced Materials for Innovation and Sustainability (AMIS) by Grenoble INP, Aalto University School of Science, Technische Universität Darmstadt, Université de Bordeaux and Université de Liège. Available online at https://amis-master.eitrawmaterials.eu/study/#impact.

Blengini, Gian Andrea; Nuss, Philip; Dewulf, Jo; Nita, Viorel; Talens Peiró, Laura; Vidal-Legaz, Beatriz et al. (2017): EU methodology for critical raw materials assessment. Policy needs and proposed solutions for incremental improvements. In *Resources Policy* 53, pp. 12–19. DOI: 10.1016/j.resourpol.2017.05.008.

BRGM (2012-2019): minéralinfo. Le portail Français des ressources minérales non énergétiques. Available online at http://www.mineralinfo.fr/.

Buijs, Bram; Sievers, Henrike; Tercero Espinoza, Luis A. (2012): Limits to the critical raw materials approach. In *Proceedings of the ICE - Waste and Resource Management* 165 (4), pp. 201–208. DOI: 10.1680/warm.12.00010.

CfPA (2018): Processing of cGMP Controlled Raw Materials: 6 Hour Online Course. Center for Professional Advancement (CfPA). Available online at https://www.cfpa.com/UpcomingCourses/PDFDisplay?PDFFolder=2018&PDFFileName=2778,OP,180419OP2778L.pdf.

CfPA (2019): Processing of cGMP Controlled Raw Materials: Extended Online Course. Center for Professional Advancement (CfPA). Available online at https://www.cfpa.com/CourseDescription/CourseDescription/0/2778.

CMI (2016): CMI Education and Outreach in 2016. Critical Materials Institute (CMI). Available online at https://cmi.ameslab.gov/about/education/cmi-education-and-outreach-2016.

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

CMI (2019a): CMI Education and Outreach. Critical Materials Institute (CMI). Available online at https://cmi.ameslab.gov/about/cmi-education-and-outreach.

CMI (2019b): CMI Education Course Inventory: Geology Engineering/Geochemistry. Critical Materials Institute (CMI). Available online at https://cmi.ameslab.gov/about/education/course-inventory-geology.

CMI (2019c): CMI Education Partner: Colorado School of Mines. Critical Materials Institute (CMI). Available online at https://cmi.ameslab.gov/about/education/course-inventory-mines#geology-eng.

CMI (2019d): CMI Education Partners Offer Courses. Critical Materials Institute (CMI). Available online at https://cmi.ameslab.gov/about/education/course-inventory.

CMI (2019e): CMI Education Resources for K-12. Critical Materials Institute (CMI). Available online at https://cmi.ameslab.gov/about/education/ed-resources-k12.

CMI (2019f): CMI Offers Webinars on Critical Materials and Rare Earths. Critical Materials Institute (CMI). Available online at https://cmi.ameslab.gov/about/education/cmi-webinars.

CMI (2019g): Other Education and Outreach Resources. Critical Materials Institute (CMI). Available online at https://cmi.ameslab.gov/about/education/other-outreach-resources.

DERA (2019): Rohstoffinformationssystem. ROSYS. Deutsche Rohstoffagentur (DERA) in der Bundesanstalt für Geowissenschaften und Rohstoffe (BGR). Available online at https://rosys.dera.bgr.de/mapapps/resources/apps/rosys/index.html?lang=en.

EIT RawMaterials (2018): The Added Value for the European Economy of Recycling of Secondary Critical Raw Material within Europe. EIT RawMaterials via RoMa - Transferring Raw Materials Knowledge to Market. Available online at https://romalearning.mondragon.edu/courses/course-v1:EITRawMaterials+TRMC005+2018/about.

EIT RawMaterials (2019a): Corporate Social Responsibility – A Life-Cycle Assessment from Prospect to Closure. EIT RawMaterials. Available online at https://courses.eitrawmaterials.eu/details.xhtml;jsessionid=B9E5A579B1C974D821500168B816ED44?vid=153&vidp=0&vp=J.

EIT RawMaterials (2019b): EIT-Labelled Master Programmes. EIT RawMaterials. Available online at https://eitrawmaterials.eu/eit-rm-academy/labelled-masters/.

EIT RawMaterials (2019c): EIT-Labelled PhD Programmes. EIT RawMaterials. Available online at https://eitrawmaterials.eu/eit-rm-academy/eit-labelled-phd-programmes/.

EIT RawMaterials (2019d): Exploration, (E)Valuation and Reporting of Raw Material Deposits. EIT RawMaterials. Available online at

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

https://courses.eitrawmaterials.eu/details.xhtml;jsessionid=B9E5A579B1C974D821500168B816ED44?vid=152&vidp=0&vp=J.

EIT RawMaterials (2019e): IDS-FunMat-Inno-2: International Doctoral School in Functional Materials & Innovation (2nd Cohort). EIT RawMaterials. Available online at https://eitrawmaterials.eu/course/ids-funmat-inno-2/.

EIT RawMaterials (2019f): Metal Recovery: An Efficient Example of Integrated Leading Technologies for Cobalt Recovery. EIT RawMaterials via RoMa - Transferring Raw Materials Knowledge to Market. Available online at https://romalearning.mondragon.edu/courses/course-v1:EITRawMaterials+TRMW012+2019/about.

EIT RawMaterials (2019g): RawMatCop Academy 2019. EIT RawMaterials. Available online at https://courses.eitrawmaterials.eu/details.xhtml;jsessionid=B9E5A579B1C974D821500168B816ED44?vid=158&vidp=0&vp=J.

EIT RawMaterials (2019h): REFER: Raw Engagement for Electronics Repair. EIT RawMaterials. Available online at https://eitrawmaterials.eu/course/refer/.

EIT RawMaterials (2019i): Reporting in the Mineral Industry - Resources & Reserves, Asset Valuation, Sustainability & Social Responsibility. EIT RawMaterials. Available online at https://courses.eitrawmaterials.eu/details.xhtml;jsessionid=B9E5A579B1C974D821500168B816ED44?vid=165&vidp=0&vp=J.

EMerald (2019): EMerald Course Content. EMerald Master Course in Resources Engineering by Liège Université, Université de Lorraine, Luleå Tekniska Universitet, Technische Universität Bergakademie Freiberg. Available online at http://www.emerald.ulg.ac.be/?q=content-and-structure.

Erdmann, Lorenz; Graedel, Thomas E. (2011): Criticality of Non-Fuel Minerals: A Review of Major Approaches and Analyses. In *Environ. Sci. Technol.* 45 (18), pp. 7620–7630. DOI: 10.1021/es200563g.

EREK (2019): Raw Materials Scanner. European Resource Efficiency Knowledge Centre (EREK). Available online at https://www.resourceefficient.eu/fr/node/487.

ETH Zürich (2015): Sustainable Materials Management: Concepts, Methods and Principles. ETH Zürich. Available online at http://www.vvz.ethz.ch/Vorlesungsverzeichnis/lerneinheit.view?semkez=2017W&ansicht=ALLE&lerneinheitId=115779&lang=en.

European Commission (2010): Critical raw materials for the EU. Report of the Ad-hoc Working Group on defining critical raw materials. With assistance of Fraunhofer ISI. Available online at http://ec.europa.eu/enterprise/policies/raw-materials/files/docs/report-b_en.pdf, checked on 1/29/2013.

European Commission (2011): Tackling the challenges in commodity markets and on raw materials. European Commission (Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, COM(2011) 25 final). Available online at http://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1433773853128&uri=CELEX:52011DC0025.

European Commission (2014): Report on critical raw materials for the EU. Report of the Ad-hoc Working Group on defining critical raw materials. With assistance of Oakdene Hollins, Fraunhofer ISI. European Commission. Brussels.

European Commission (2017a): Methodology for establishing the EU list of critical raw materials. Guidelines. With assistance of Gian Andrea Blengini, Darina Blagoeva, Jo Dewulf, Cristina Torres de Matos, Claudia Baranzelli, Constantin Ciupagea et al. Available online at https://publications.europa.eu/s/dkxK, checked on 9/10/2017.

European Commission (2017b): Study on the review of the list of Critical Raw Materials. Criticality Assessments. With assistance of Deloitte, BGS, BRGM, TNO. Luxembourg, checked on 9/21/2017.

Glöser, Simon; Tercero Espinoza, Luis; Gandenberger, Carsten; Faulstich, Martin (2015): Raw material criticality in the context of classical risk assessment. In *Resources Policy* 44, pp. 35–46. DOI: 10.1016/j.resourpol.2014.12.003.

Graedel, T. E.; Barr, Rachel; Chandler, Chelsea; Chase, Thomas; Choi, Joanne; Christoffersen, Lee et al. (2012): Methodology of metal criticality determination. In *Environmental science & technology* 46 (2), pp. 1063–1070. DOI: 10.1021/es203534z.

Graedel, T. E.; Harper, E. M.; Nassar, N. T.; Nuss, Philip; Reck, Barbara K. (2015): Criticality of metals and metalloids. In *Proceedings of the National Academy of Sciences*, p. 201500415. DOI: 10.1073/pnas.1500415112.

Granta Design (2014): Release Notes for CES EduPack 2014. Granta Design Ltd. Available online at https://downloadfiles.grantadesign.com/pdf/CESEduPack2014releasenotes.pdf.

Granta Design (2019a): CES EduPack Data. Granta Design Ltd. Available online at https://grantadesign.com/education/ces-edupack/data/.

Granta Design (2019b): Information Pack for Educators. Available online at https://grantadesign.com/education/support/ces-edupack-support/information-pack-for-educators/.

Granta Design (2019c): Sustainable Development Edition. Granta Design Ltd. Available online at https://grantadesign.com/education/.

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

Granta Design (2019d): Teaching Resources. Industrial Case Study: Electric Cars - Sustainability and Eco Design. With assistance of Claes Fredriksson, Fernando Coelho, Luca Petruccell. Granta Design Ltd. Available online at https://grantadesign.com/teachingresources/caseseen18/.

Granta Design (2019e): Teaching Ressources. Poster: Sustainable Development. With assistance of Mike Ashby. Granta Design Ltd. Available online at https://grantadesign.com/teachingresources/pstsdven16/.

Helbig, Christoph; Wietschel, Lars; Thorenz, Andrea; Tuma, Axel (2016): How to evaluate raw material vulnerability - An overview. In *Resources Policy* 48, pp. 13–24. DOI: 10.1016/j.resourpol.2016.02.003.

IDS-FunMat (2019): Welcome to IDS-FunMat-INNO. International Doctoral School in Functional Materials and Innovation (IDS-FunMat-INNO) by KIC EIT-Raw Materials. Available online at http://idsfunmat.u-bordeaux.fr/index.php/ids-inno-home.

ISM (2019): Online Learning. Institute for Supply Management (ISM). Available online at https://www.instituteforsupplymanagement.org/files/education/onlinelearningcatalog.pdf.

JRC (2019): EU Science Hub. Raw Materials Information System (RMIS). Available online at https://rmis.jrc.ec.europa.eu/.

Liège Université (2019): Solid Waste and ByProducts Processing. Université de Liège. Available online at https://www.programmes.uliege.be/cocoon/20192020/en/cours/GEOL0315-1.html.

McCullough, Erin; Nassar, Nedal T. (2017): Assessment of critical minerals. Updated application of an early-warning screening methodology. In *Miner Econ* 30 (3), pp. 257–272. DOI: 10.1007/s13563-017-0119-6.

Moss, R.L; Tzimas, E.; Willis, P.; Ahrendorf, Josie; Tercero Espinoza, Luis; Thompson, Paul et al. (2013): Critical Metals in the Path towards the Decarbonisation of the EU Energy Sector. Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies. JRC - Institute for Energy and Transport; Oakdene Hollins; Fraunhofer ISI (JRC Scientific and Policy Reports, EUR 25994 EN). Available online at http://setis.ec.europa.eu/publications/jrc-setis-reports/jrc-report-critical-metals-energy-sector.

NRC (2008): Minerals, critical minerals and the U.S. economy. National Research Council. Available online at http://www.nap.edu/catalog.php?record_id=12034.

PiLog Group (2018): Material Criticality Analysis. PiLog Group. Available online at https://piloggroup.com/SA/material-criticality-analysis.php.

RM@Schools (2019): Raw MatTERS Ambassadors at Schools. RM@Schools European Educational Project. Available online at http://rmschools.isof.cnr.it/index.html.

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

SINReM (2019): Programme. Master Program in Sustainable and Innovative Natural Resource Management (SINReM) by Technische Universität Bergakademie Freiberg, Uppsala Universitet, Ghent University. Available online at https://sinrem.eu/programme/.

SUMA (2019): Programme Paths & Fees. The Master Programme on Sustainable Materials (SUMA) by KU Leuven, Montanuniversität Leoben, University of Trento, INP Grenoble, University of Milano-Bicocca. Available online at https://www.master-suma.eu/study/#paths.

SusCritMat (2018a): Impressions from the first SusCritMat Winter School. Les Diablerets, Switzerland, January 14-19, 2018. Sustainable Management of Critical Raw Materials (SusCritMat). Available online at https://suscritmat.eu/wp-content/uploads/2018/12/WS-report.pdf.

SusCritMat (2018b): SusCritMat Short Course 2018. Sustainable Management of Critical Raw Materials (SusCritMat). Available online at https://suscritmat.eu/suscritmat-short-course-2018/.

SusCritMat (2019a): SusCritMat Homepage. Sustainable Management of Critical Raw Materials (SusCritMat). Available online at https://suscritmat.eu/.

SusCritMat (2019b): SusCritMat Short Course 2019. Sustainable Management of Critical Raw Materials (SusCritMat). Available online at https://suscritmat.eu/suscritmat-short-course-2019/.

SusCritMat (2019c): SusCritMat Summer School 2019. Sustainable Management of Critical Raw Materials (SusCritMat). Available online at https://suscritmat.eu/suscritmat-summer-school-2019/.

SusCritMat (2019d): Video Learning Content. Sustainable Management of Critical Raw Materials (SusCritMat). Available online at https://suscritmat.eu/video-learning-content/.

TNO, EY, HCSS, Leiden University (2017): Grondstoffenscanner. Pilot. Netherlands Organisation for Applied Scientific Research (TNO), Ernst & Young (EY), Hague Centre for Strategic Studies (HCSS), Leiden University. Available online at https://acc.grondstoffenscanner.nl/#/.

TU Delft (2019): Waste Management and Critical Raw Materials. Delft University of Technology. Available online at https://online-learning.tudelft.nl/courses/waste-management-and-critical-raw-materials/.

Università di Trento (2016): Recycling and Sustainable Materials. Università di Trento. Available online at https://www.esse3.unitn.it/Guide/PaginaADErogata.do;jsessionid=7C36C4C99C09D1C9009F3FF2DCC13696.esse3-unitn-prod-06?cod_lingua=eng&ad_er_id=2016*N0*N0*S2*38752*92075&ANNO_ACCADEMICO=2016&mostra_percorsi=S.

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

University of Augsburg (2019): Industrial Ecology. Universität Augsburg. Available online at https://www.wiwi.uni-augsburg.de/en/cir/incoming-infos/courses/showcourse.php?id=463.

University of Basel (2017): Universität Basel Masterstudium: Sustainable Development. Universität Basel. Available online at https://www.unibas.ch/de/Studium/Studienangebot/Studiengaenge-faecher/Sustainable-Development.html.

University of Surrey (2019): Engineering Materials and Sustainability - 2020/1. University of Surrey. Available online at https://catalogue.surrey.ac.uk/2020-1/module/ENG1078.

US DoE (2011): Critical Materials Strategy. With assistance of Diana Bauer, David Diamond, Jennifer Li, Michael McKittrick, D. Sandalow, P. Telleen. U.S. Department of Energy. Available online at https://energy.gov/sites/prod/files/DOE_CMS2011_FINAL_Full.pdf, checked on 5/22/2017.

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation