# Teaching Resources on the Sustainable Management of Critical Raw Materials

*Trainer's Manual for*
Process Models based on LCA

March 2020

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

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# 1 Context and Introduction to Training

This booklet is supplementing the teaching materials and the set of further supporting booklets that have been developed to support teachers in conducting training courses related to the sustainable management of critical raw materials.

SusCritMat aims to educate people from Master's student level up, both in industry and academia about important aspects of sustainable critical raw materials. In a novel concept, it introduces courses on these complex and interdisciplinary topics in a modular structure, adaptable to a variety of different formats and accessible to both students and managers in industry. These courses will develop new skills, which will help participants to better understand the impact and role of critical raw materials in the whole value chain; enabling them to identify and mitigate risks. Understanding the bigger picture and the interconnected nature of global business and society is increasingly necessary to and valued by industry.

SusCritMat is an EU-funded project that brings together the technical and pedagogical expertise of leading educational institutions and business partners. It uses and creates teaching materials which can be combined into different course formats.

The collection of training manuals presents the key messages related with the sustainable management of critical raw materials in three major sections:

- Introduction to criticality
- Analysis of criticality
- Solutions for sustainable management

In particular, the solutions part will be in the focus. The intention is to underline the possibilities that are available to approach and implement a circular economy for critical raw materials and the products bearing these. Doing so the concrete actions, i.e. the things that can be done, are highlighted, instead of only mentioning all sorts of associated problems or barriers in the context of CRMs.

The overall goal of the SusCritMat project is to qualify lecturers to teach the topics themselves. Therefore, the teaching resources do not only provide an introduction and improved insight into selected thematic issues, but also deliver a set of teaching materials "ready-to-use".

- Learning targets that will be reached after having taught the courses.
- Presentations on the specific topics including also notes on how to present the slides and key messages.
- Group work exercises including the task or question to work on, if applicable further reading on the methodology and the solutions in case of tasks requiring calculations.
- Assessment questions and the correct answers for each specific topic.
- Additional reading for each topic.

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## 1.1 Training Materials List

The *SusCritMat project* developed the following teaching materials:

| |
|---|
| **Basics** |
| Critical Resources for Emerging Technologies |
| Criticality |
| Supply Chain Resilience |
| Supply Risk Factors |
| **Circularity** |
| Circular Economy |
| Characterizing the Urban Mine |
| Circular Business Models |
| Waste Management and Recycling Potential |
| Closing Loops on Product Level |
| **Governance** |
| Geopolitical Aspects |
| Metals & CRM Scenarios |
| Restricted Substances Legislation |
| **Impact on Society and the Environment** |
| Sustainability Assessment |
| Responsible Mining |
| Responsible Sourcing / Certification |
| Environmental Aspects |
| Sustainable Materials Usage |
| CRM and Sustainable Development |
| **Tools** |
| MFA - Material Flow Management |
| Good Use of Data |
| LCA – Life Cycle Assessment |
| **Process Models based on LCA** |

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## 1.2 Suggested timetable

The agenda contains a recommended timing for the lecture and exercises. However, depending on the pre-existing knowledge or group size the time can be extended.

- Lecture: 45 minutes (Overview of Process Model Based LCA for large scale Circular Economy Systems - using HSC Chemistry Software – Figure 1)
- Exercise: (Process Model Based LCA - using HSC Chemistry Software – DEMO for aluminium recycling)
- 45 minutes – Demo type, if the participants do not have laptops with HSC installed
- 105 minutes (45min + 15min break + 45min) - Workshop type, if participants have own laptops with HSC installed. The tool is HSC Sim 10.
- Recap and discussion: 20 minutes.

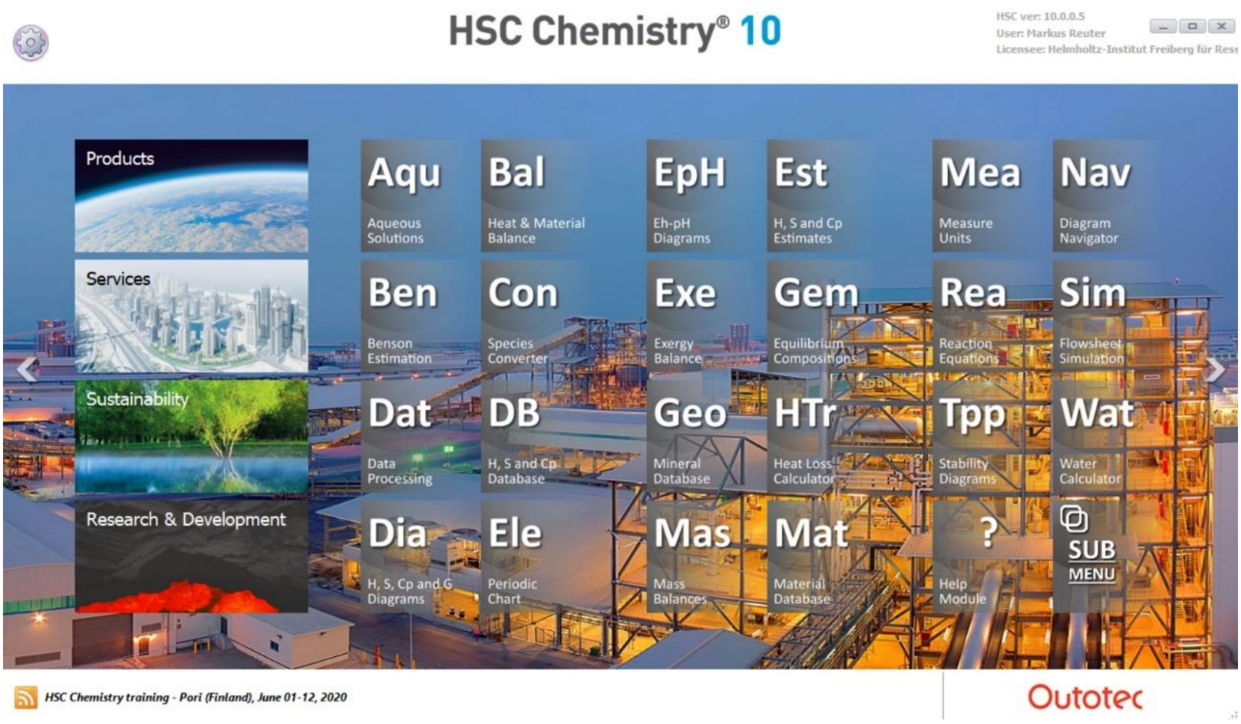

Figure 1: HSC Sim 10 digital simulation platform

## 1.3 Simulation based analysis of large circular economy systems

Environmental footprints are usually calculated for the products of the manufacturing industry, like phones, cars, lamps, etc. Lot of work has also done to evaluate LCA values of different energy sources. However, much less attention is given to the role of process industry, which produces raw materials for the manufacturing industry. The environmental footprints of the metals and chemicals are highly dependent on the process technology and the metallurgical infrastructure, which is used in the primary and secondary production of materials.

The losses from the system are numerous as Figure 2 shows, in fact the system spirals downward, due to the significant dissipation of exergy as well as energy. The key objective of this module is to show students this complexity and the quantification of the losses.

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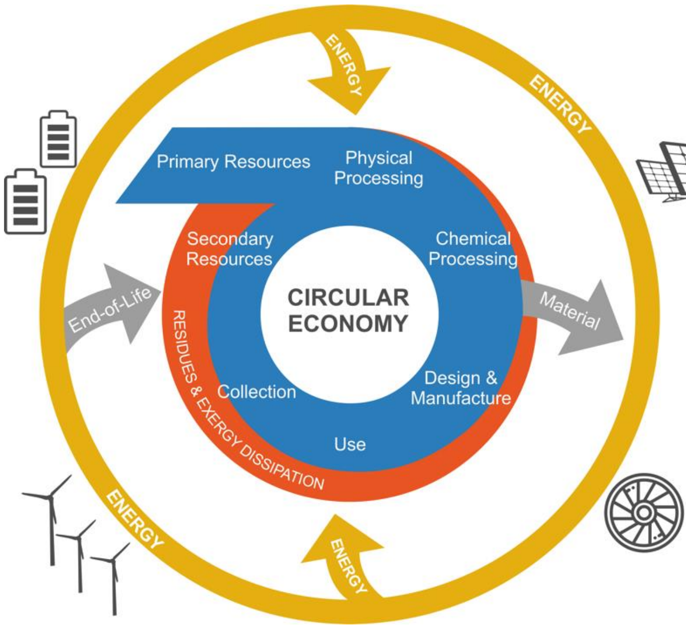


Figure 2: The downward spiral of the circular economy – linking the energy and resource systems on a fundamental thermodynamic simulation basis.

The true question thus to be answered is: "How to limit the losses, the dilution, dissipation, etc. of materials, elements, compounds, exergy, energy etc. from the system.

This training module review the role and impact of the process industry on the primary LCA data used in the manufacturing industry. Also, analysis of systems is done on the basis exergy.

This module shows the very complex nature of multi-material and metal processing in the circular economy value chain. To analyse these systems requires sophisticated tools as shown below, that create a digital platform that combines different tools to analyse the depth of the system.

The key objective of this module is SIMULATION BASED FOOTPRINTING OF SYSTEMS and will be covered by:

- a discussion and presentation providing an overview of system simulation for the circular economy;
- an overview of some of the tools and platforms;
- a class-based exercise to develop viewpoints and lessons learned for learners: aluminium recycling is provided as a cases study to understand the effects of impurities, dilution etc. on the recycling rate, exergy dissipation and energy losses during processing;
- an example, which will be used to calculate exergy and energy losses as well as recycling rates; and
- key guiding topics for teachers in the class-based exercise are given in the notes in the presentation.

Figure 3 below shows how different platforms are connected to provide the detailed answers to analyse very large systems as shown in the figure further below for the circular economy of a solar PV system.

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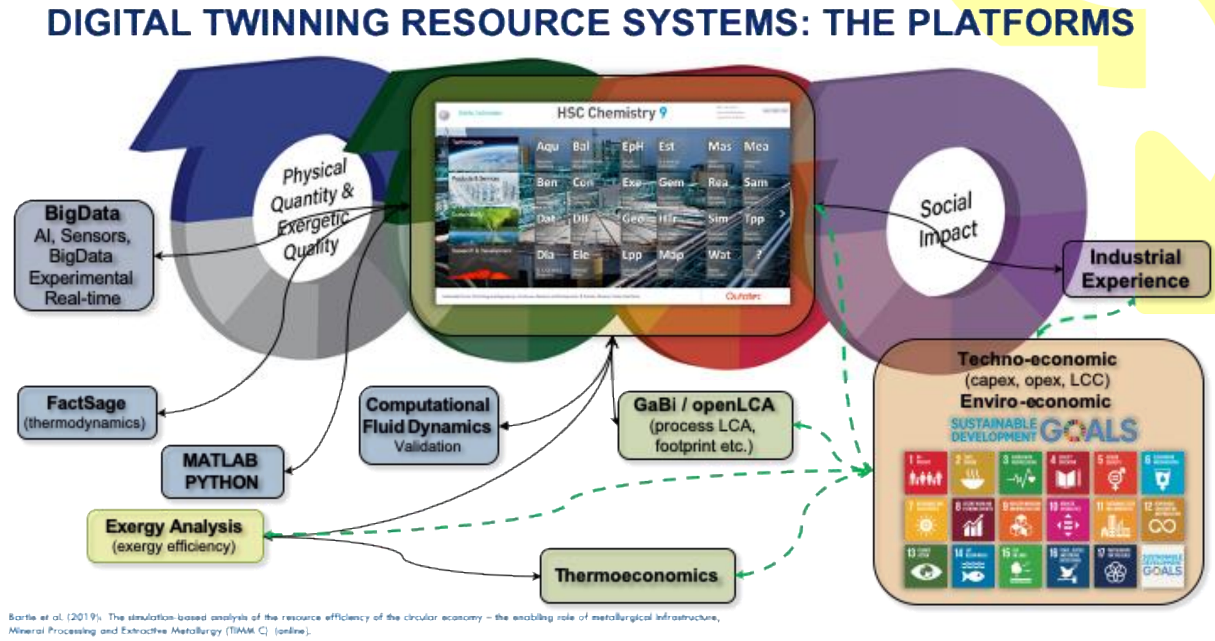


Figure 3: Digital platform linking different stakeholders with different digital tools.

## 1.4 Learning Objectives

Systems of the circular economy are complex as Figure 4 below would suggest.

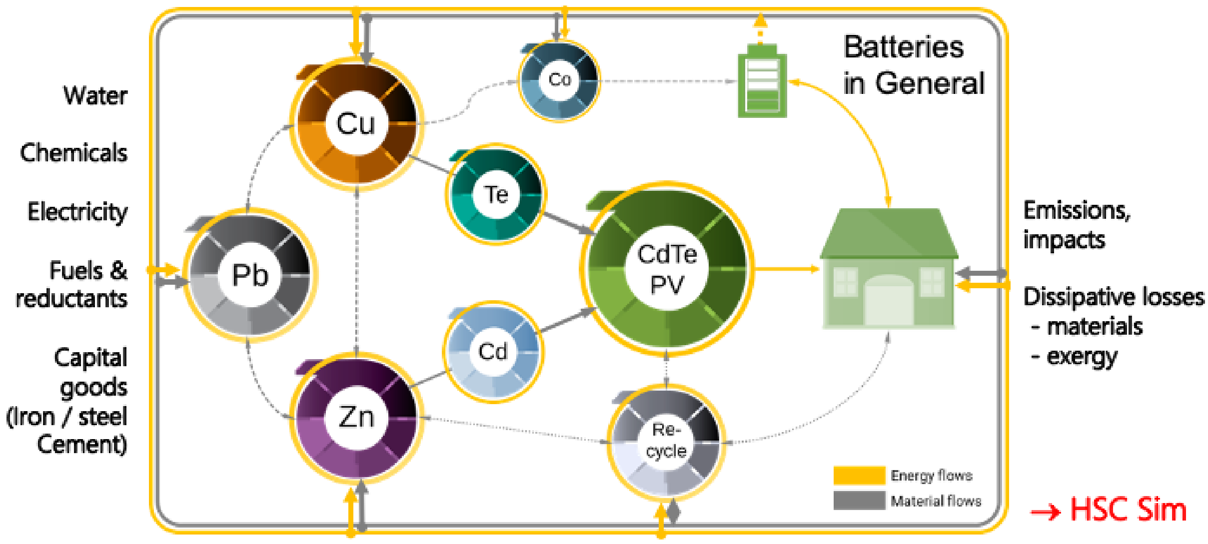


Figure 4: Linking different metallurgical processing infrastructures with PV and battery technology while including their use and recycling, while linking these also to product design.


eit RawMaterials ACADEMY
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After following this course, the learner should be able to:

- Understand the complexity of multi-material processing in the circular economy.
- Critically and quantitively assess the limitations and opportunities of the circular economy on the basis of a number of examples.
- Use a simulation tool that realistically predicts the flow of materials through the circular economy as a function of:
    - Complex products and their full composition of functional materials
    - Complex flowsheets and reactor technology
    - Thermochemistry and the complex thermodynamic interactions between compounds and materials in the circular economy.
- Perform simulation-based life cycle analysis of CE systems.
- Understand the concept of exergy-based dissipation as a necessary measure of resource efficiency.
- Through the aluminium alloy recycling case study understand the effect of dilution and complex mixtures of material (plastics, oxidation, alloying elements) on limiting the recycling of materials in the circular economy.

Figure 5 shows after sorting of a general series 8xxx alloy of a particular thickness the amount of pure aluminium and alloying elements that have to be added to provide exactly the alloy required in the case below for the cast alloy AA355.0.

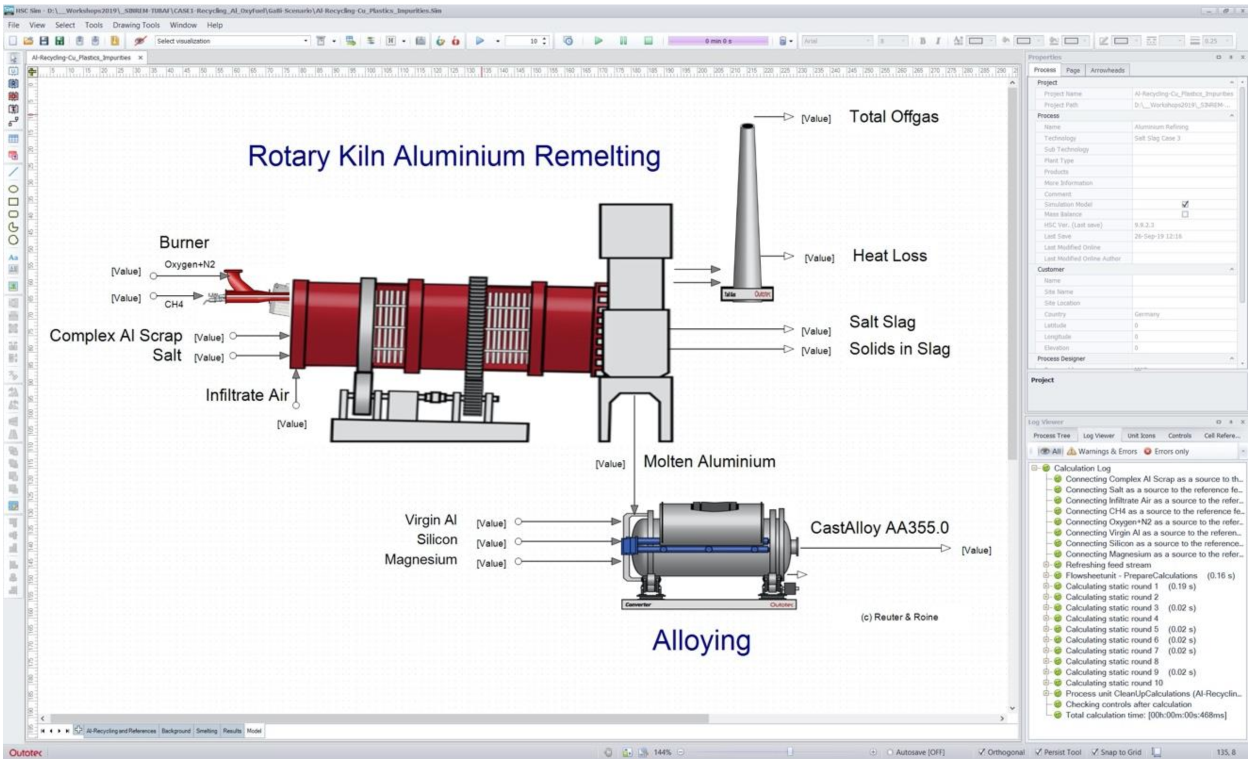


Figure 5: HSC Sim 10 simulation for recycling of unclean aluminium scrap to a specific AA355.0 alloy using free energy minimization.

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For more complex alloys and mixtures, the optimization situation for minimizing resource efficiency becomes challenging with many alloying elements have to be tuned to the correct amount for particular alloys. Many of the elements in the figure below are critical resources/elements. This is shown below in Figure 6 for producing an alloy 8011 from an average composition of 8xxx.

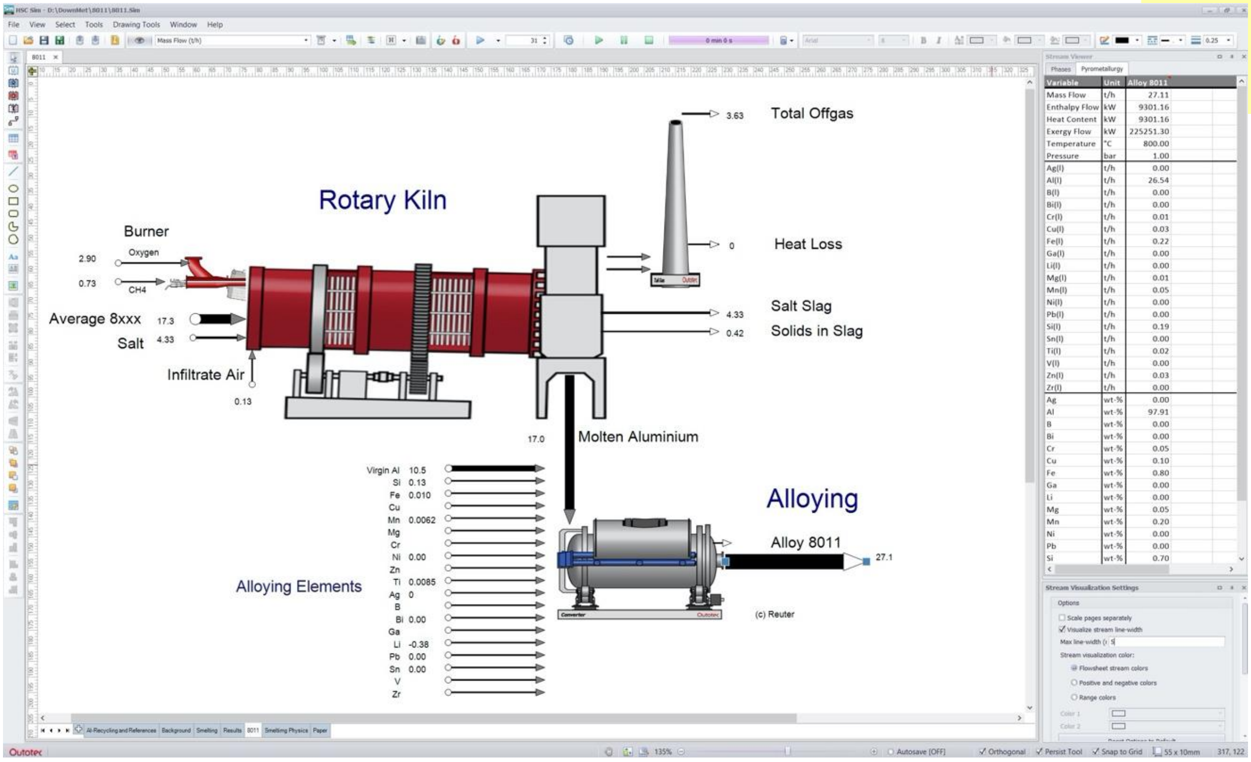


Figure 6: HSC Sim 10 for recycling of average aluminium 8xxx scrap to a specific 8011 alloy using free energy minimization.

A key learning outcome is to show what the effect is of plastics and impurities as well as the morphology of the scrap i.e. its shape and thickness, as this plays a key role in understanding the losses of aluminium due to alumina ($Al_2O_3$). The large the surface the larger the losses! The graph below in Figure 7, created by the class example shows this loss (x-scale is logarithmic – see table left for values).

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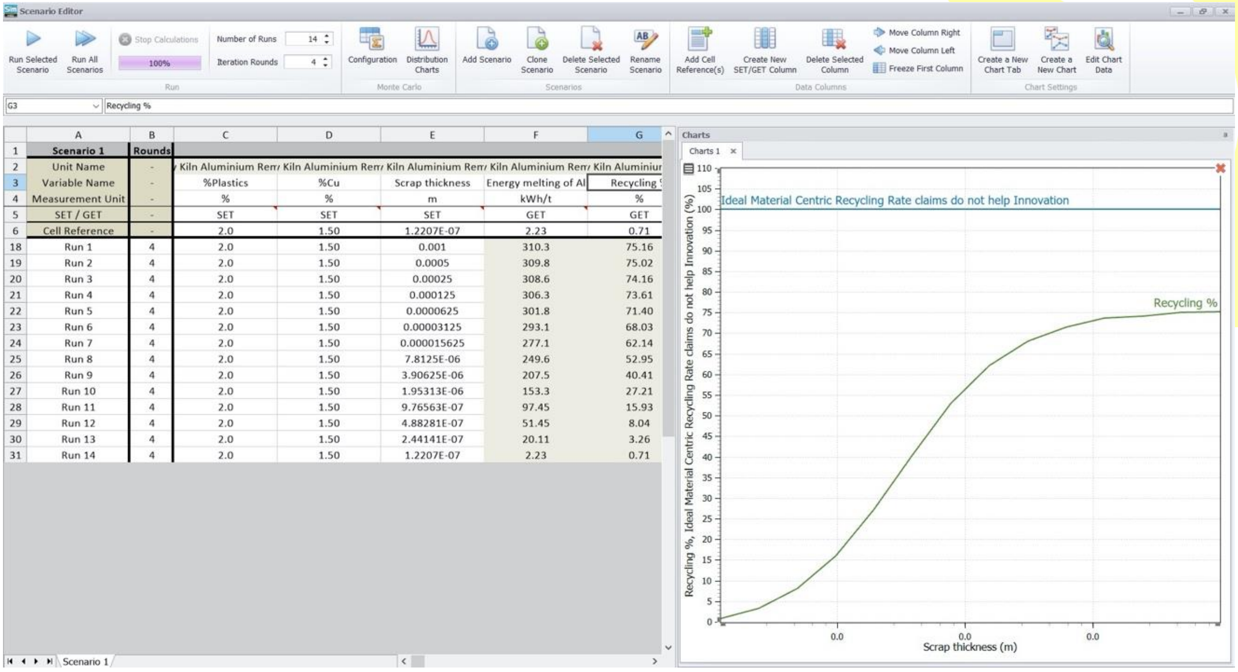


Figure 7: HSC Sim 10 simulation to determine the recycling rate of unclean aluminium scrap (includes plastic coating of different scrap thickness) to a specific alloy type.

In addition, the important contribution of this module is not only to analyse the systems with the LCA tool in HSC Sim 10, but also using exergy dissipation as a measure as shown in Figure 8 below for producing an alloy 8011 from an average composition of 8xxx.

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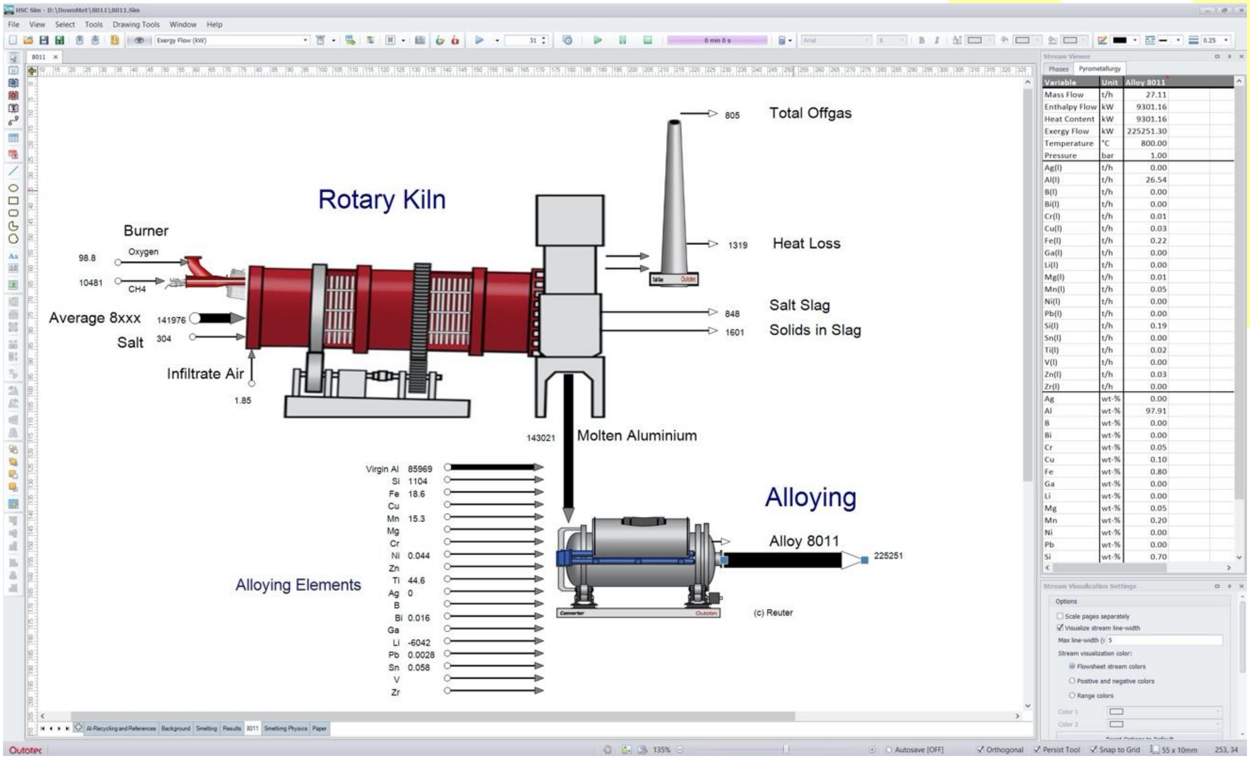


Figure 8: HSC Sim 10 simulation to determine the recycling rate of average 8xxx aluminium scrap (includes plastic coating of different scrap thickness) to a specific alloy type 8011 (note all the alloying elements that have to be managed, many of them critical elements).

Figure 9 shows that models exist in HSC 10 that link the physical separation models such as eddy current with aluminium alloy remelting. A resource index on the basis of exergy has been developed.

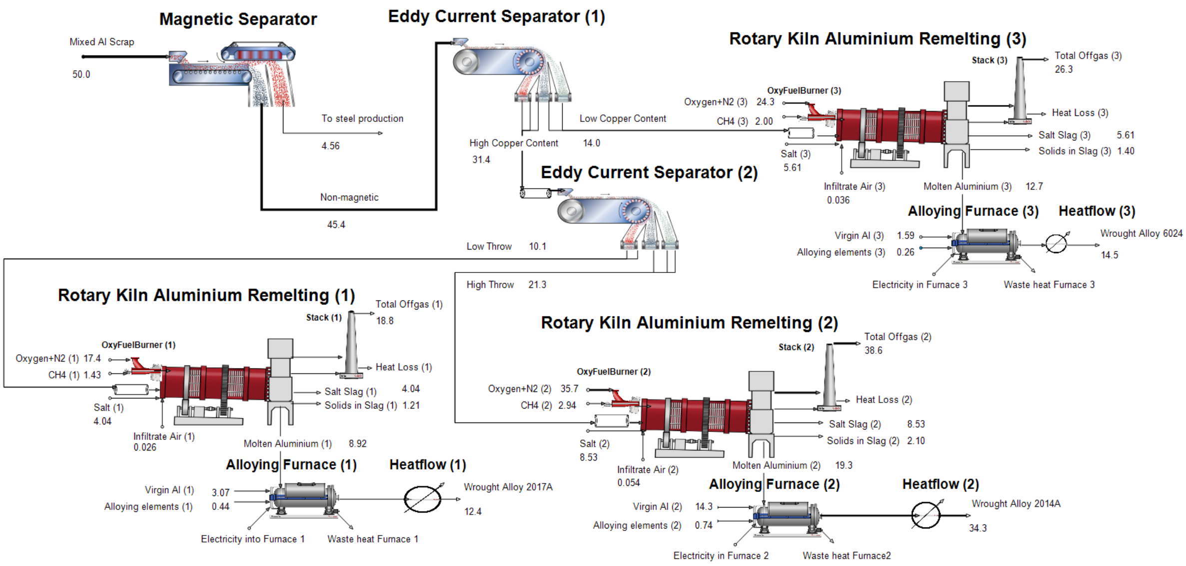


Figure 9: HSC Sim 10 simulation model linking physical separation to alloy production (Hannula et al., 2020).

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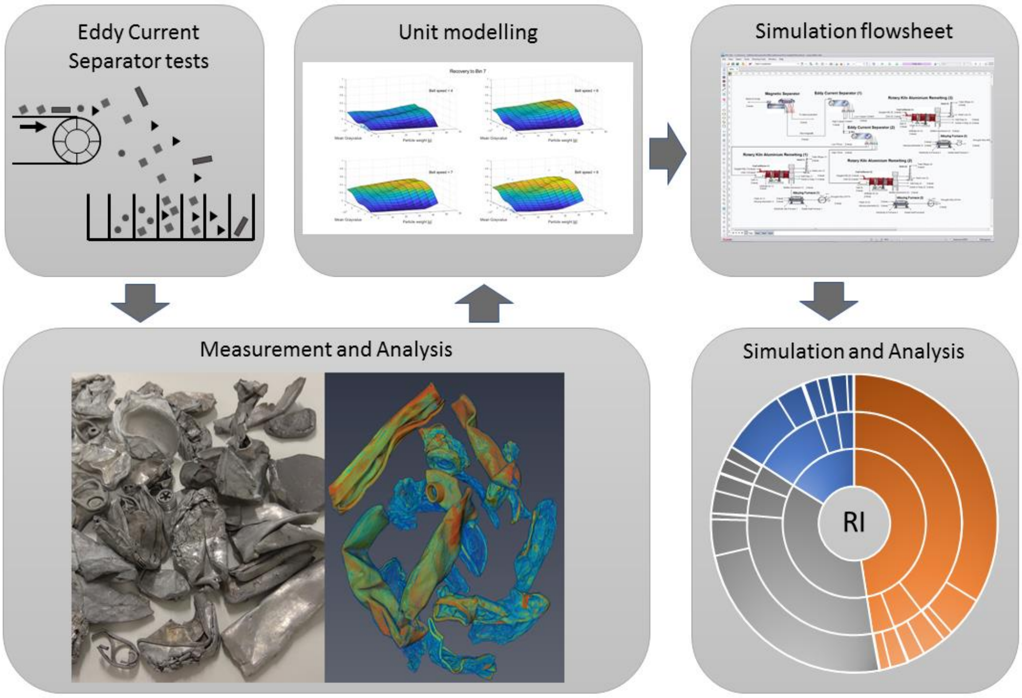


Figure 10: HSC Sim 10 simulation model linking physical separation to alloy production: linking x-ray tomography to scrap analysis and calibration of models and linking to alloy production (Hannula et al., 2020).

## 1.5 Additional Reading

The following reading material is provided in the HSC Sim simulation file and a list of references.

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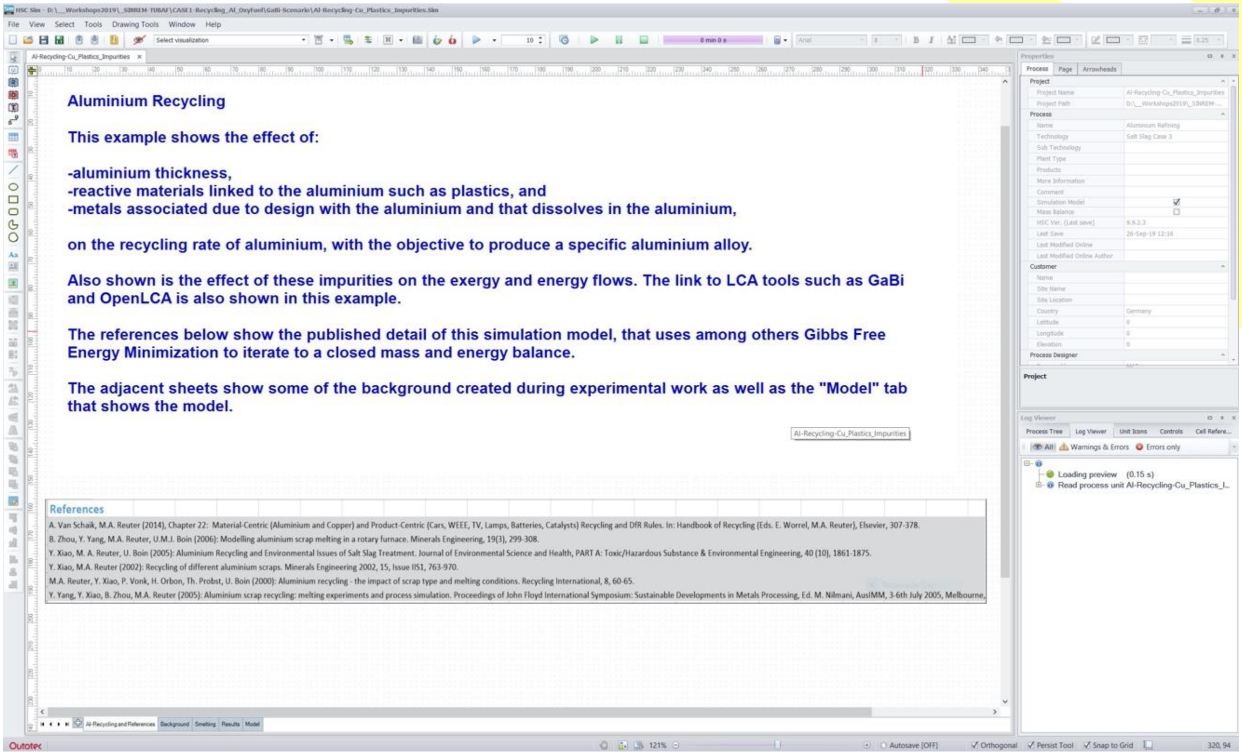



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- E. Worrell, M.A. Reuter (2014): Handbook of Recycling, Elsevier BV, Amsterdam, 595p. (ISBN 978-0-12-396459-5).


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- M.A. Reuter, C. Hudson, A. van Schaik, K. Heiskanen, C. Meskers, C. Hagelüken (2013):United Nations Environmental Protection (UNEP) Report "Metal Recycling: Opportunities Limits Infrastructure" report: http://www.resourcepanel.org/reports/metal-recycling

## 2 Slides and Notes

- Slides are supplied in pptx format with annotations.
- The simulation model in HSC Sim 10 is at the basis to show complexity during recycling. This course must be performed using the supplied HSC Sim model for aluminium recycling.

## 3 Assessment Questions

- **What are the main differences between the manufacturing and process industry?**

Answer 1 (correct): Manufacturing industry delivers physical products using raw materials and energy coming from the process industry. Manufacturing is based on mechanical engineering sciences and process industry is based on chemistry, metallurgy, mineral processing and energy technology.

- **Are the primary LCA values of the raw materials and energy constants?**

Answer 1 (correct): No, they depend heavily on many factors. For example, electricity LCA data depends on the production methods.

- **Which factors determine the primary LCA values (environmental footprint) of the raw materials and energy?**

Answer 1 (correct): Process technology (recoveries/grades/availability/energy efficiency/exergy efficiency…), energy sources used, origin of the primary raw materials (ore), ore grade/impurities, plant location (production country), mining technology, recycling technology, amount of recycling, transportation distances, transportation method, by-products,…

- **Give some examples of the recycling within the last 2000 years**

Answer 1 (correct): Most of the copper, gold, silver and iron produced within the last 2000 years is still circulating in our society. Elements do not go out of fashion; these may be recycled as long as the costs permit to unravel the dilution that inevitably occurs and the processing losses that are dictated by thermodynamics, kinetics and technology type.

- **Can primary metal production processes be utilized in recycling?**

Answer 1 (correct): Traditionally many metal and chemical production processes are based on internal recycling. For example, the copper process profitability is often based on efficient recovery of the by-products like gold, silver, platinum, nickel, selenium, etc. The same


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procedures can also be utilized in external recycling to recover valuable metals from the electronic and other scrap.

- **What are the benefits of process model based LCA evaluation in process design?**

Answer 1 (correct): Process key performance indicators like metal recoveries, product grades, energy efficiencies, CAPEX and OPEX are defined in the process design stage. The process environmental footprints can also be optimised at the process design stage, when these process models are linked with the environmental footprint software. The second main benefit is that crucial elemental and energy balances are automatically maintained in the process modelling software, then also ensure these balances in the LCA software results.

- **What are the benefits of process model based LCA evaluation in process operation?**

Answer 1 (correct): In metal and chemical production the raw material compositions and energy sources are continuously changing. Process key performance indicators, like metal recoveries, product grades, energy efficiencies, OPEX may be optimized using digital twins of the plants where process models are brains (calculation engines) of the digital twins.
The process environmental footprints may also be continuously optimized, if these process models are linked to LCA software packages. In addition, if LCA data are not available in the databases for new or every specific process chains, these LCA data can be estimated by rigorous flowsheets, also for novel new processes.

- **What stages does the Life Cycle of metals consist of?**

Answer 1 (correct): Primary mining (ore, coal, crude oil), Processing (metals, chemicals, energy), Manufacturing (physical products), Usage (consumption), Re-use (re-cycle), Recycling/Disposal. The target is to minimize disposal and maximize recycling.

- **What parameters affect the recycling of aluminium?**

Answer 1 (correct): Aluminium is a reactive metal and therefore reacts with oxygen, carbon, nitrogen, sulphur, phosphorous to name a few. These all contribute to losses. These elements are brought into the process as no furnace (unless vacuum technology) can be airtight, there will always be burn-off, while a variety of other elements may enter the system through the unclean scrap. Furthermore, elements in the scrap associated with the aluminium dissolve in the aluminium and therefore virgin (pure electrolytic) aluminium has to be added to dilute impurities to produce the required alloys.

- **How does surface to mass ratio of aluminium affect the recycling rate?**

Answer 1 (correct): The larger the surface area per mass/volume of aluminium the lower the recycling rate as the oxidized surface of aluminium as $Al_2O_3$ becomes ever large mass percentage of the scrap therefore the lower the aluminium metal recovery in total. In addition, there will always be burn-off in the remelting reactor therefore more losses.

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## 4 Acknowledgements and Authors

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The following authors have contributed to prepare the complete teaching material kit and intend to provide an overview of major topics surrounding the sustainable management of critical raw materials:

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## 5 Citation

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# 6 Disclaimer

The teaching materials within the SusCritMat project have been prepared with great care and experienced several revisions. Nevertheless, the consortium assumes no liability for the topicality, completeness and correctness of the content provided.

In case you have suggestions or other feedback how to improve the materials, we value your opinion: Please contact us via the project webpage https://suscritmat.eu/contact/.

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