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Property-based modelling and simulation of mechanical separation processes using dynamic binning and neural networks

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ABSTRACT

To fully understand the possibilities and the limits of the Circular Economy (CE), a comprehensive model taking into account its different stages (product design, mechanical pre-processing, metallurgy, etc.) is required. A crucial aspect is to understand the inevitable losses at different stages of recycling. The complexity of the material streams in mechanical separation processes requires a detailed description of particles and their properties to successfully simulate unit processes. This paper presents a new approach that connects measurement-based particle properties to statistical modelling and simulation of mechanical separation processes. The proposed approach combines particle tracking with the generalization ability of neural networks. Above all, it advances the present particle binning and tracking methods utilizing property-based binning rather than liberation-based binning for modelling purposes of complex systems. In order to demonstrate the new approach, this paper uses Mineral Liberation Analysis (MLA) data from magnetic and gravity separation processes of a complex ore. The proposed approach can be integrated into present simulation platforms such as HSC Sim.

1. Introduction

In order to fully appreciate the possibilities – and to acknowledge the limits – of Circular Economy (CE) in terms of material flows, recyclabilities and recycling efficiencies, a comprehensive understanding of CE's different stages is required. This includes understanding the link between the complexity of modern consumer products, and the effects of this complexity on the efficiency of the stages of recycling (carried out by different stakeholders), as depicted in Fig. 1. As shown, a detailed understanding, and a common description of the "mineralogies", of both the ore particles and the man-made function materials in products, is required to harmonize the simulation through the complete system. If these properties are captured sufficiently well in unit separation models, the system can be optimized based on fundamental particle properties, and the associated thermodynamic information.

In practice, recycling is carried out in several stages. First, the recycling is based on waste classes, like Waste Electrical and Electronic Equipment (WEEE), Plastics, etc. After this, a common practice (especially in the WEEE recycling) is to comminute the End-of-life-products (EOL) to maximize the liberation of different materials. This is followed by the separation of the resulting particles in multiple steps, based on their physical properties like density, magnetic properties, shape, etc. The objective of this stage is to get relatively clean material streams enriched in certain elements or substances. These material streams are further treated in specialized facilities, e.g. metallurgical plants. In metallurgical processing, many of the losses are controlled by thermodynamics, and complexity of the incoming material stream due to affinities of materials and metals to each other. The recovery, and the energy consumption of the metallurgical stage is thus determined by the quality of the incoming material stream.

If all materials and metals were perfectly separated to their own fractions during physical separation, CE would be (almost) truly circular. The physical separability is thus the limiting factor for recyclability, and it is determined both by the product design, and the effectiveness of the separation strategies and machines. In mechanical pre-processing, the separation efficiency is linked to the complexity of the particles to be separated. This complexity is caused by the product design, and while comminution-phase aims to liberate all materials, 100% liberation can never be achieved, as shown by Castro et al. (2005). For example, a product that only consists of copper or iron is almost perfectly recyclable, and no mechanical separation will be required. If a product consists of both copper and iron, losses are practically inevitable. This, in turn, decreases the quality of the recyclate streams. The extent to which the quality of these streams decreases,

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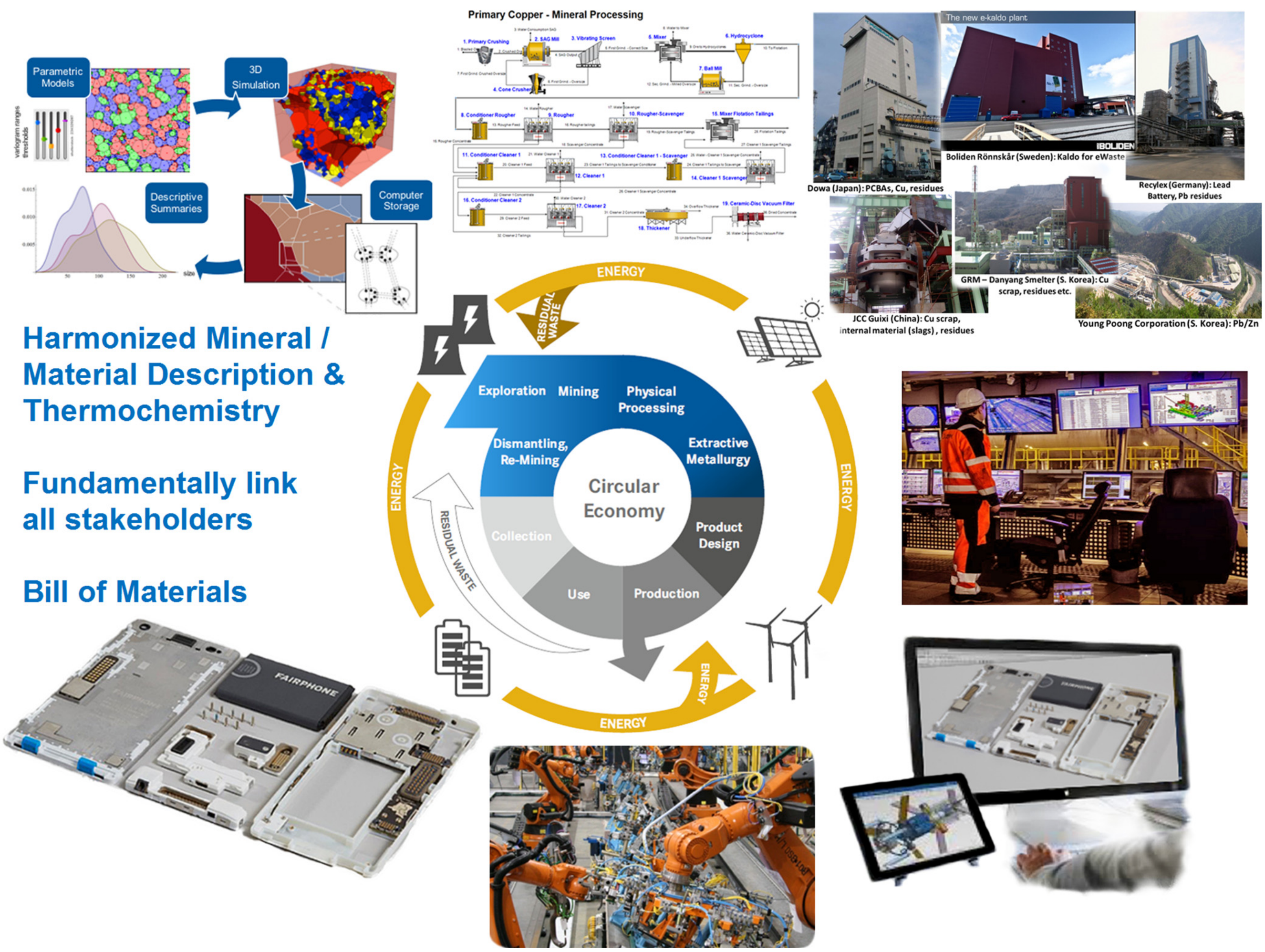

Fig. 1. The CE – Key challenge to harmonize the renewable energy and processing industries through digitalization to optimize resource efficiency – of key importance is a detailed understanding of the particle properties in mineral processing as well as in modules of products.

depends on the structure of the product, which ranges from a perfectly separable mix of iron and copper to a practically inseparable alloy. The aim of this paper is to quantify the effect of the particle structure on the physical separability in mechanical pre-processing, and to develop a framework that uses the observable particle properties to develop predictive unit separation models for simulation purposes.

The fundamental understanding of CE, as promoted in this paper, is discussed by UNEP (2013), where also the product complexity is linked to the losses at different recycling stages. Fairphone (2017) is an unfortunately rare exception, where this detailed approach is understood and applied to a commercial product. It is crucial that the effect of the product structure on the separability of its components be quantified. The analysis should allow to model and simulate full effect of the product design on the recycling of the product (Reuter, 2016).

When considering the recyclability of modern consumer products, the models need to be detailed enough to be able to capture the distribution of metals and materials through the system. Furthermore, a deep understanding of the processes and the interconnection of product design to recycle streams, and consequently, to the separation efficiency, is required. This means understanding the effect of product design on the quality of the recyclates and further understanding the recyclability of these recyclates; how the distribution of materials and metals in the complex particles affects the achievable recycling rates and optimal recycling strategies.

In order to address the simulation of complex systems, one needs to understand and digitalize the unit operation models in the Circular Economy. To achieve this, the paper includes:

- An introduction to a method that creates predictive unit separation models, using observable properties in particle-level detail. The method is a combination of some elements of the traditional particle tracking by Lamberg and Vianna (2007) and neural networks, which have been used in minerals and metals field for many years, as already discussed by Aldrich et al. (1994).
- Characterization of multi-dimensional property space in condensed form to suit simulation purposes. This characterization maximizes the use of information from the measurement data for modelling purposes.
- Harmonization of the particle description for CE. To create CE-wide simulation models, which include minerals, metals, and materials, a uniform particle description is required for simulation models including both primary and secondary resources.

Due to the limitations in the available data from scrap particles, this paper uses MLA data from mineral processing as an example to demonstrate the ability of the new approach to predict the recovery of particles based on their relevant properties. While applying this technique to secondary resources is the aim of the following papers, the examples shown here demonstrate that this approach can be applied to the modelling and simulation of primary resources, especially considering more and more complex ores.