2016 TMS EPD Distinguished Lecture Award

Digitalizing the Circular Economy

Circular Economy Engineering Defined by the Metallurgical Internet of Things

MARKUS A. REUTER

Metallurgy is a key enabler of a circular economy (CE), its digitalization is the metallurgical Internet of Things (m-IoT). In short: Metallurgy is at the heart of a CE, as metals all have strong intrinsic recycling potentials. Process metallurgy, as a key enabler for a CE, will help much to deliver its goals. The first-principles models of process engineering help quantify the resource efficiency (RE) of the CE system, connecting all stakeholders *via* digitalization. This provides well-argued and first-principles environmental information to empower a tax paying consumer society, policy, legislators, and environmentalists. It provides the details of capital expenditure and operational expenditure estimates. Through this path, the opportunities and limits of a CE, recycling, and its technology can be estimated. The true boundaries of sustainability can be determined in addition to the techno-economic evaluation of RE. The integration of metallurgical reactor technology and systems digitally, not only on one site but linking different sites globally *via* hardware, is the basis for describing CE systems as dynamic feedback control loops, *i.e.*, the m-IoT. It is the linkage of the global carrier metallurgical processing system infrastructure that maximizes the recovery of all minor and technology elements in its associated refining metallurgical infrastructure. This will be illustrated through the following: (1) System optimization models for multimetal metallurgical processing. These map large-scale m-IoT systems linked to computer-aided design tools of the original equipment manufacturers and then establish a recycling index through the quantification of RE. (2) Reactor optimization and industrial system solutions to realize the "CE (within a) Corporation—CEC," realizing the CE of society. (3) Real-time measurement of ore and scrap properties in intelligent plant structures, linked to the modeling, simulation, and optimization of industrial extractive process metallurgical reactors and plants for both primary and secondary materials processing. (4) Big-data analysis and process control of industrial metallurgical systems, processes, and reactors by the application of, among others, artificial intelligence techniques and computer-aided engineering. (5) Minerals processing and process metallurgical theory, technology, simulation, and analytical

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tools, which are all key enablers of the CE. (6) Visualizing the results of all the tools used for estimating the RE of the CE system in a form that the consumer and general public can understand. (7) The smart integration of tools and methods that quantify RE and deliver sustainable solutions, named in this article as circular economy engineering. In view of space limitations, this message will be colored in by various publications also with students and colleagues, referring to (often commercial) software that acts as a conduit to capture and formalize the research of the large body of work in the literature by distinguished metallurgical engineers and researchers and realized in innovative industrial solutions. The author stands humbly on the shoulders of these developments and their distinguished developers. This award lecture article implicitly also refers to work done while working for Ausmelt (Australia), Outotec (Finland and Australia), Mintek (South Africa), and Anglo American Corporation (South Africa), honoring the many colleagues the author has worked with over the years.

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I. INTRODUCTION

A. *Summary*

Circular economy (CE) is defined here in terms of the metallurgical Internet of Things (m-IoT). This is the digitalized Web of Metals (WoM) or, in other words, the system integrated material production (SIMP). Its digitalization provides the real-time detail that quantifies the three pillars of sustainability: social, environmental, and economical. This is termed "circular economy engineering" (CEE), *i.e.*, the digitalization of the CE, using among others the theory and technology of minerals processing, metallurgy, recycling, computer-aided engineering (CAE), and product design. This provides the basis for the estimation of the metrics of resource efficiency (RE) and, hence, provides a direction for innovation and also enables the m-IoT.

B. *Circular Economy*

The CE paradigm is high on the EU political agenda.[1] One of the key drivers of a CE is metallurgy and recycling and the understanding of entropy in each of its facets. However, the present reality is that consumer products are complex, consisting of many technological and critical and functional materials/elements.[2] These create complex recyclates with high entropy, which are rather challenging to recycle well and, in the process, decrease the entropy again. In addition, these products often have a short life span and are intensively produced and consumed, thus challenging the recovery of these metals from large volumes of complex recyclate mixtures. Controlling the entropy creation during collection is also of significant importance.

If consumer products were simple and constructed from one material only (and then most likely rather aesthetically unattractive as well as lacking all complex functionality required by the modern products), recyclates would obviously be 100 pct pure. CE would then be an easy and simplistic endeavor, as entropy creation is low. This is, however, not the reality of our society, which is driven by complex (consumer) products. If society would reduce drastically its consumption, the complicating issues of complex society in a CE would become trivial, as these can be mitigated; in fact, a CE would become irrelevant. Perhaps this may be the only way into the future.

This implies the variability of products and materials demands a dynamically agile metallurgical processing infrastructure to absorb and process into high-quality products as many combinations of complexly linked materials. Therefore, the metallurgical infrastructure is critical to control entropy creation. This means that for a CE to be realized, a high-tech adaptive base metal (with refining infrastructure),[3] light metal, and steel metallurgical infrastructure, which interlinks all metallurgical processing industries, must be available and nurtured. This is system integrated metal and material production. Policy must acknowledge the key importance of the metallurgical infrastructure for achieving a CE.

C. *Digitalizing and Innovating the CE*

Realizing the full potential, challenges, and fundamental innovations to achieve a CE system requires an understanding of the social, technological, economic, and environmental opportunities and limits thereof.[4,5] The innovations, digitalization tools, and challenges to move toward a CE, include, among others, the following.

(1) *Product centric recycling (PCR)*[4] captures the full nonlinear effects of the recovery and losses of all materials, elements, strategy, technology, and critical raw materials on each other in addition to the contamination of the materials on each other. This is analogous to processing of complex polymetallic minerals and simultaneously ensuring that all elements, metals, and gangue are processed to economically valuable environmentally benign final products.

(2) *Analytical and simulation tools of minerals and metallurgical processing*, such as artificial intelligence (AI), CAE, computer-aided design (CAD), computational fluid dynamics (CFD), discrete element methods (DEM), Design for Recycling (DfR), sustainability, RE and Design for Resource Efficiency (DfRE), Design for Sustainability (DfS),

life-cycle assessment (LCA), flowsheeting, plant design, plant operation, plant service, process simulation, plant and system optimization, and thermodynamic and kinetic simulation, for the theoretical analysis of the CE system are key. The innovation lies in developing these tools within the context of CE for optimizing metallurgical systems and estimating their RE.[6–9] Ten DfR Rules have been developed and explained in detail by Van Schaik and Reuter.[9]

(3) *Mineralogy of recyclates are key to determine the recycling index (RI) of products* and have to be quantified in such a manner that thermodynamic and physical properties can be derived for them. This makes it possible to use simulation[9–11] tools that can represent and optimize the complete CE system. The innovation, therefore, is to consider all properties of the recyclate particles and flows in the CE system simulation, including properties such as enthalpy, entropy and energy,[11] alloy and material composition, conductivity, color, magnetic susceptibility, density, shape, odor, near-infrared properties, interlinkages of materials in scrap particles, brittleness, and ductility. These must all form part of the predictive simulation and optimization models.

(4) *Quantifying RE* of the CE for both products and recycling in a manner that acknowledges the complexity of a PCR approach, which takes all materials of the consumer product (from the urban mine) into consideration. This emulates the geometallurgy applied to the analysis of complex minerals from a geological mine. The innovation is that primary and secondary processing is considered equivalent, ensuring that all materials are recovered, as is done in classical mineral processing. We have coined this PCR.[4]

(5) *Real-time big-data approaches* must be used to calibrate metallurgical, recycling, and CE system models that create a basis to optimize the processing chain while providing the necessary detail to calculate capital expenditure (CAPEX) and operational expenditure (OPEX) in addition to the environmental footprint.[11] The innovation is that the simulation basis provides the true economic potential of the CE as it rigorously maps all recoveries, losses, and costs incurred due to the recovery and losses.[12,13] This simulation basis determines the baseline recovery rate and potential for specific products applying a PCR approach. This highlights the actions to take to innovate the CE system.

(6) *A real-time feedback loop to DfRE and DfR*[9] and CE system configurations for real-time grade monitoring of recyclates is required using suitable multisensors to estimate all possible contaminants and valuables in them, hence linking this to high-quality material and metal production processing.

(7) *Energy efficiency (EE) and material efficiency* [material efficiency in industrial production focuses on the amount of a particular material needed to produce a particular product (UNEP, http://www.unep.org)],[14,15] of which the RI[11] forms an important part, should be optimized as a function of product, recycling, and processing infrastructure design in order to fully reveal the opportunities and limits of the CE system.

(8) *Adaptive CE system approaches*[10–12] must be the basis of innovative CE business models. These aid the design of a closed-loop system for material use preventing the loss of materials from the economy and into the environment including innovations to producer responsibility and new product ownership models. This provides a basis for developing innovative collection and organizational approaches to increase the amount of sorted End-of-Life (EoL) goods (thus unmixed and, therefore, controlling entropy), collected and reported EoL goods, and their subsequent reuse, recovery, and closed-loop recycling gleaning from the feedback from limits and critical issues in recycling learned from industry process simulation. The innovation is to minimize mixing and thus decrease entropy creation, the key parameter to be optimized.

(9) *Innovative and disruptive business models* will need to be connected to material science and metallurgical process engineering, underpinning policy with physics and economics creating the field of CEE. This links, for example, CAE and process control platforms while creating RE economically viable CE solutions.

(10) *Engage end users* (consumers and businesses) in both the design of collection and in the testing of potential approaches. Their acceptance to recycled and reused products can be increased, especially also if they are informed in a simple manner *via* visual methods to show the effect on RE of their choices.

D. *An Adaptive and Agile Metallurgical Processing Infrastructure*

Therefore, the key challenge is to understand the role and digitalization of an adaptive infrastructure and process technology to innovate the true potential of CE thinking. Understanding the agile adaptive and flexible multimetal process metallurgical infrastructure of the m-IoT is one of the main underlying topics of this article. Digitalizing it by linking all stakeholders is the vehicle. Note that the steel industry has made major advances in system integration of their various high-tech fully integrated technologies, which supply high-quality steels to high-end users.[16] This is similar for the high-tech integration of copper smelters producing a multitude of high-tech metals using sophisticated refining infrastructure.[17] M-IoT, however, refers to a level higher, *i.e.*, linking steel, aluminum, and base metal production facilities forming the complex WoM.[4,7] The WoM permits the capture of as many metals as possible that enter the metal production system through minerals as well as EoL products and, therefore, has the ability to maximize RE through its versatility, agility, and flexibility in metallurgy. System agility is a keyword for realizing CE.

Using the optimization of minerals processing flotation plants of the author as a starting point for system optimization in this CE centric discussion,[13] the complex interconnected WoM[3,4,7] will be shown as an example of industrial ecology (IE)[6] to quantify the complexity of the WoM. Therefore, digitalizing the complexity of the WoM, which is an integral part of IE in terms of PCR and metallurgical processing, will be the basis for defining m-IoT. This is one of the backbones for realizing the m-IoT, which will be a key enabling driver of the CE system.

E. *Is the m-IoT and Its Inherent Digitalization a Key Enabler of the CE?*

In this article, that reflects my award lecture, I will limit myself, in view of space, to color in the message with various publications I have been involved in. Having said this, this article is respectfully dedicated to the numerous great metallurgists on whose shoulders I stand. I use the numerous software tools and thus implicitly their innovative creators and all those that have breathed life into them through their research, data, methods, *etc.* as main references to the message. These are, in fact, the true fabric and platforms of CEE. In the Acknowledgments, I name mentors and colleagues who have had the biggest impact on my path.

Reading through this article, please keep in mind the statement: *''Process metallurgy is a key enabler for a CE and will help much to deliver its noble goals through digitalizing the complete WoM.''* The questions thus to ask are as follows: Is the previous statement in itallics true? Can industrialization, Mother Earth, and nature be harmonized to achieve ''sustainability'' in our present consumer society? What are the other key factors that play a role in enabling CE? Can entropy be quantified for all steps in the CE system to understand its true (sometimes rather obvious) limitations?

In summary: Understanding RE within a CE paradigm, therefore, is key for sustainability, revealing the true opportunities and limits crucial for a sustainable future. This contribution implicitly shows that we should refrain from hiding behind sweet sounding ideologies, such as cradle to cradle, that neglect limiting rigorous physics details and continue business as usual, while conveniently forgetting the hard facts of theory and industrial practice that process metallurgy so beautifully reveals. The frank and clear analysis of the true potential of CE through the application of the discussed CEE tools and their techno-economic reality may possibly produce inconvenient answers for the future, hence showing us how many fewer resources we will have to consume in view of meeting climate change goals. However, understanding and quantifying its true potential in addition to its philosophical depth will deliver the gifts of CE thinking and sustainable systems redesign.

II. THEORETICAL BASIS OF A CE

A. *Summary*

Process metallurgy, its metallurgical processing systems, and its infrastructure are key enablers of a CE. They are, in fact, some of the key foundations also for understanding entropy creation in the CE system. Various aspects of this network of metallurgical processing will be depicted in this section in the context that forms the fabric of m-IoT.

B. *Geological and Urban Mines*

Modern consumer products are characterized by complexly linked functional metals, nanometals, and micrometals as well as alloys linked to functional inorganic materials and plastics.[5] These materials form the fabric of modern society applied in various applications including renewable energy applications, eMobility, information technology, buildings, transport, and consumer goods. Establishing the limit for RE of the complex and highly interconnected systems of a CE shown by Figure 1 requires a detailed understanding (*i.e.*, the separation physics and related techno-economics) of each stakeholder in the system and how the mentioned products flow together with their materials through the CE system. The product's functionality determines the complex selection of materials, which are joined by various methods (additive manufacture, layered, glued, welded, *etc.*), which directly affect the recyclability of the materials. Therefore, there is a direct link between product complexity and the entropy of contained materials; thus, there is the possibility of economically recovering the metals in the CE system.

Often the economic, ecological, and social values of the materials in modern products are determined by their ''in-use value.'' Only functionality, aesthetics, safety, durability, and reduced energy consumption are considered. While more value is being given presently to the recyclability of products (and their contained materials), there is a lot of work to be done to empower the user to make informed decisions about their use. Showing the user in simple ways what products have the lowest environmental and social impacts is of paramount importance to us process engineers.

The term m-IoT of the interconnected material production system shown by Figure 1 is an integral and necessary requirement to ''close the loop'' and maximize the RE. Minerals, both geological and from the urban mine, are the tie-entity that glues all aspects of Figure 1 together. Figure 2 explains how ''mineral'' and thus product centric expertise and understanding are key in permitting rigorous simulation linking the different stakeholders shown by Figure 1.

Advances have been made in geometallurgy, but metallurgical process modeling needs considerable innovation to be truly dynamic and predictive, linking all aspects of Figure 1 in real-time. Linking product design to metal and material losses from the system is the true innovation and challenge. However, this requires considerable understanding of process metallurgy; not only fundamental depth is required of entropy, *e.g.*, simulation, digitalization, and process control, but also the industry perspective of a design engineer will contribute to the digitalized link and the practicalities of metallurgical processing technology.

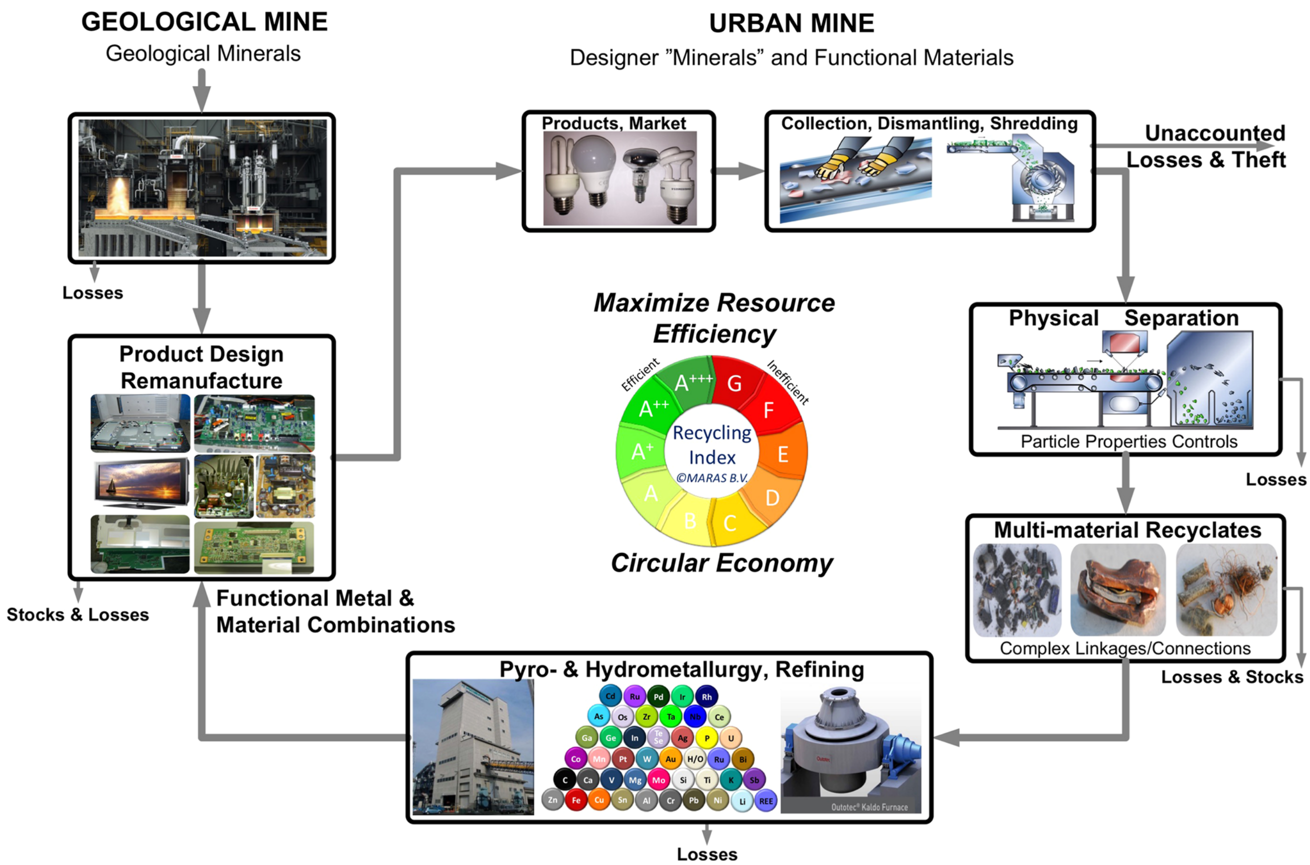

Fig. 1—Achieving a CE requires minimizing the losses or, in other words, maximizing RE from each step. Each stakeholder in the m-IoT must contribute in such a way that the complete CE system must operate as sustainably as possible.[11,15]

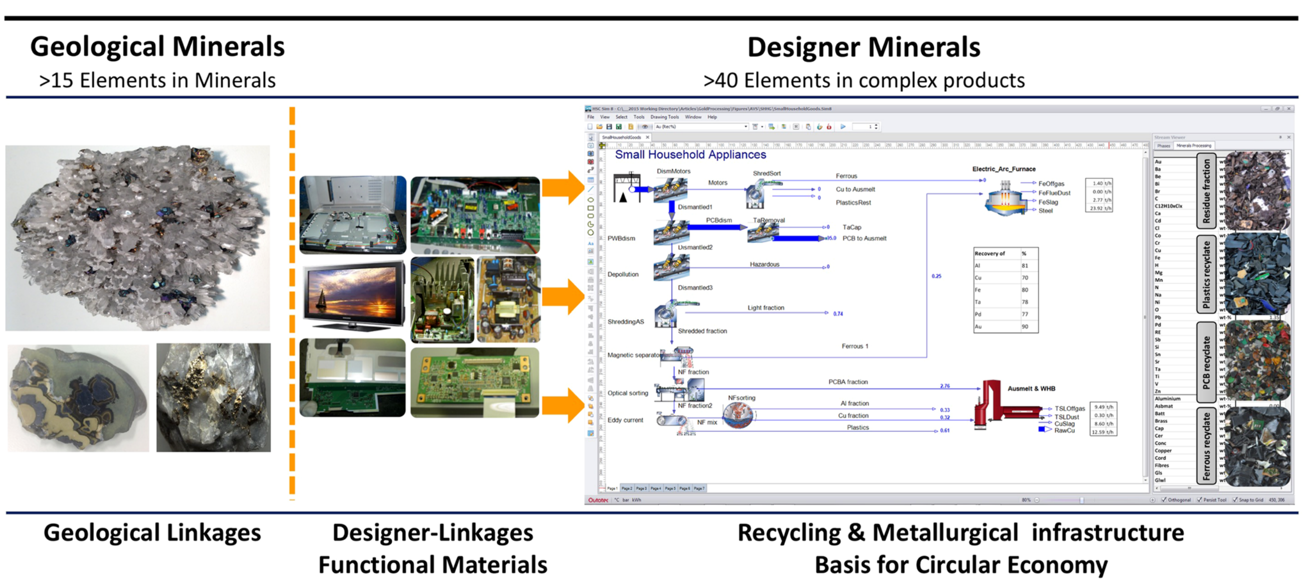

Fig. 2—Geological minerals are complex (left), but designed urban minerals are even more so. This challenges the recovery of the elements in best practice process technology, the use of digitalization tools that quantify RE and achieve a resource efficient CE society. PCR and system analysis are required and form the heart of CE system greenprinting.[11]

C. *Tools to Quantify RE*

Figures 1 and 2 suggest implicitly that the social and environmental value of materials and metals can only be properly determined by digitalizing all aspects. Linking of all the stakeholders of m-IoT requires the following detailed expertise and tools.

(1) *System engineering*[10,15–32]: Understanding the complex interlinkage of metals and materials in the complex WoM is crucial for optimizing RE. The future availability of materials and technology elements feeding into sustainable products and society are of great interest to realize the CE. System engineering tools, both steady state and dynamic modeling approaches are significant tools to understand the WoM.

(2) *System dynamics*[13,15,25,29]: Different product lifetimes (from building materials to consumer products), economics and metal prices, availability and agility of metallurgical infrastructure, substitution, legislation, geographical aspects, new products and their functionalities, *etc*. all have a profound impact on the dynamics of the flows of metals and materials. Their geological and functional linkages connect these dynamics in the products as well as in the metallurgical reactors. Thus, crucial in understanding the WoM is also its dynamics, not only on a metal-by-metal basis (thus material centric) but above all also on a mineral and product centric level that recognizes complex "mineralogy" in its full thermodynamic complexity.

(3) *Process control*[28,30,33]: Modeling system dynamics requires a deep knowledge of process control. Not only is this of crucial importance for understanding the feedback loops of the CE recycling systems, it is also of key importance for optimizing, controlling, and simulating metallurgical processing reactors in real time. This permits optimizing RE to the limits of what is thermodynamically and thus economically possible. This brings into consideration the CEE toolbox, which includes thermodynamics, kinetics, mass and heat transfer, particle flow, environmental impact analysis,[26] and exergy analysis,[26] and links it to the bigger picture of the CE system. This will enable real-time RE estimation of the CE system, a key area of development for the future, especially to optimize CE and inform the consumer and society at large of its impact.

(4) *Minerals and metallurgical process engineering*[34–38]: It is key to be able to optimally operate each of the unit operations in the feedback loop of Figure 1 in order to maximally recover all metals and materials and, thus, to understand entropy. A keen understanding of particle properties and thus minerals processing is a key aspect. Understanding the system of recycling and metal production establishes a detailed overview of all the intricacies of m-IoT. This enables a realistic first-principles description of all the intricate flows for metallurgical processing using various thermodynamic tools (thus entropy) and recycling technology subject to market conditions.

(5) *Knowledge of product design*[7]: Understanding the relationship between product design, process metallurgy, and recycling is vitally important to bridge these presently still essentially key missing links. CAE and CAD must be linked to recycling to be able to predict metal and energy recovery and waste creation/prevention. Product functionality dictates how and which materials are connected to each other, which may and often does challenge the recovery of all elements. Thus, the dictum, "One wins some metals and therefore loses others subject to the laws of physics but dictated by the product designer," should always be kept in mind, as it is always different depending on the mix of materials.

(6) *Legislation and knowledge transfer*[5]: This is crucial for CE. Informing and teaching the consumer the complexity of the modern consumer products while visualizing in simple ways the effect and limits of the insatiable demands of consumerism on the RE of a CE.

(7) *Societal and behavioral impact*: Understanding the aspects that affect, for example, consumer purchasing behavior, collection, and presorting of EoL products, which all impact the entropy at the entry point at EoL, for instance.

D. *Quantifying the RE of a CE*

With these tools, it is possible to link the materials processing and metallurgical process engineering fields to product design, enabling what is termed CEE, which can then help to quantify and provide the following.

(1) *Opportunities and limits of a CE*[39]: With detailed and fundamentally based data on all impacts, CAPEX and OPEX can be derived to determine the technological and related economic limits of the CE system.

(2) *Inform legislation and societal impact*[5,11]: The rigorous CEE approach provides a basis for quantifying the RE of the CE system on a process engineering first-principles basis. This provides the original equipment manufacturers (OEMs) with a fundamental basis to supply RE products to society while understanding their impact on the CE system. Linking CEE to the formulation of environmental legislation as well as disruptive CE business models is of critical importance and innovation.

(3) *Inform resource efficiency (iRE) and knowledge transfer*[5,11]: The development of innovative applications (apps) and visualizing the results of complex simulation models in simple-to-understand visualizations is crucial to empower society to innovate informing RE.

(4) *Environmental impact*[26,40,41] *and RI*[11]: M-IoT is a detailed process metallurgical first-principles approach, which enables the integration of methodologies such as LCA and simulation-based RI calculation[26] into CAE and CAD. The results

provide the consumer with transparent information on products detailing the impacts of all stakeholders depicted in Figure 1.

The "sustainable" m-IoT of the CE system depicted by Figures 1 and 2 should be in balance with nature. All losses and flows to nature should be understood well in their full mineralogical and compositional detail to ensure that their impact can be evaluated and thus minimized or even best stopped as far as this is possible.

III. METALLURGICAL INTERNET OF THINGS

A. *Summary*

In the present time and age, all conducted research and development should quantify its societal and environmental impact. It must be pitched within the bigger sustainability picture; thus, its social and environmental consequences must be made visible. This is most certainly valid for materials research; thus, environmental and societal impact for newly designed materials within consumer products should be known in the CE paradigm. A larger systemic picture should always be at hand to evaluate the consequences of the actions of engineers, material scientists, OEMs, and society throughout the life of the product. The impact of contained materials and associated embodied energy must be quantified and made known to the consumer. M-IoT will be the fundamental basis for this discussion.

B. *Definition of m-IoT*

The complex interaction of technology, stakeholders connecting the WoM, and materials is reflected by Figures 1 and 2. This complex network of the digitalized WoM is called the m-IoT in the context of this article, its digitalization the m-IoT. Figure 3 succinctly describes the intent of m-IoT and, hence, the innovation to be achieved by this approach. It shows the exploration of the limits of Figure 1, *i.e.*, m-IoT in a CE paradigm on the basis of the mineralogy depth shown by Figure 2, and understanding the limits (and its RE), as shown Figure 3. Thus, the simulation of the complete system and development of the techniques and tools to further provide the much-needed fundamental basis for green-printing, linking stakeholders, and control of the system[44] comprise the m-IoT. The spinoff from this is the optimization of products and their DfR, goods-services, policy formulation, and the innovation required to substantially lower the footprint of the system and explore. This will help us not only understand rigorously the limits of CE society in terms of system structure but also the technology within the system; thus, it will help to innovate the system. So the question should be asked: "Can metallurgy and technology deliver a CE?"

Figure 4 shows that Pillar 2 models are packaged into Pillar 1 large-scale simulation and system models in order to be able to realize an m-IoT approach to measure, quantify (both in terms of RE and economics), and control a CE (Pillar 3).

In order to be able to achieve the quantification and the digitalization of the m-IoT, various research and

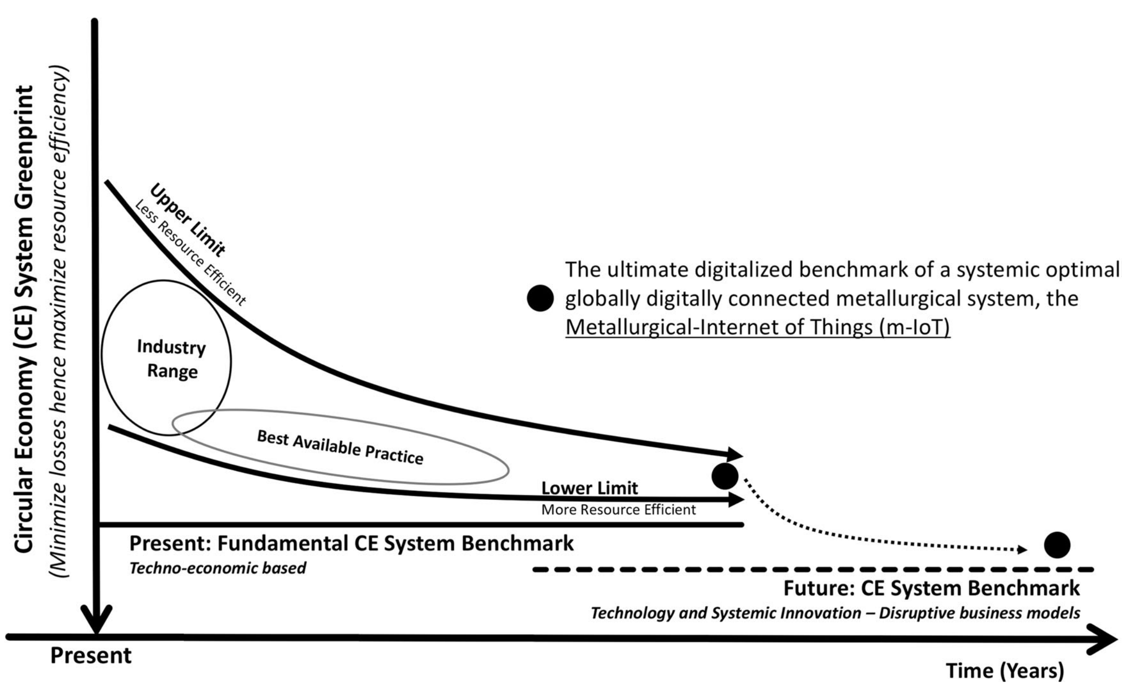

Fig. 3—Quantifying and innovating sustainability on a simulation basis and measuring this relative to what is systemically, technologically, and economically possible is key for realizing a CE.[11,42–44]

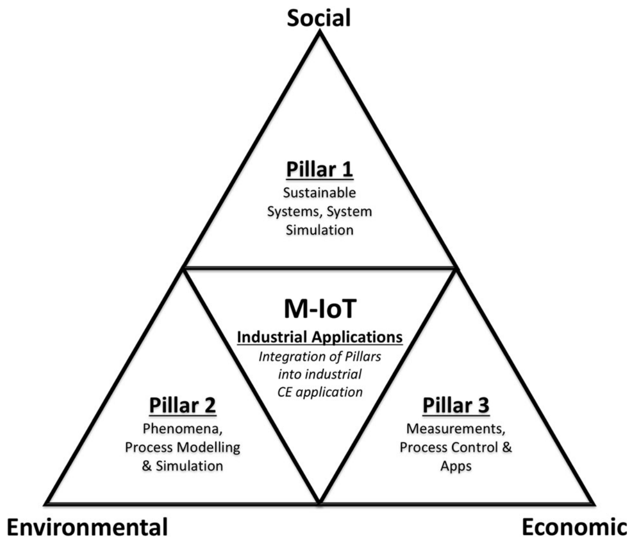

Fig. 4—Integration of Pillars 1 through 3 to reach m-IoT while embracing the drivers of sustainability.

development will be required, as reflected by Pillars 1 through 3 in Figure 4, all embedded and embraced in sustainability (social, economic, and environmental). Also of importance is the development of analysis tools and sensors that can be used to calibrate the unit models from industrial materials, recyclates, residues, scrap, *etc*. This is where big data comes into play—from a large body of poorly defined data, these unit operation models have to be calibrated. Figures 1 and 2 give some indication of the type of mineralogy data one is speaking of, which are hardly measureable, presently with large variances for many of the defining properties.

The research mentioned in Pillars 1 through 3 of Figure 4 will be directed to quantify RE and help to develop further the suite of digitalization techniques and tools required to do so. In many cases, the unit operation models to be used in this simulation are nonexistent or not predictive. Several of these methodologies are mentioned in Figure 5, and some will be elaborated below based on the author's past developments of these and use within the metallurgical process industry. However, the transformation of these models to the designed "minerals" of the urban mine is still a barren area that needs to be filled to be able to totally simulate the system, as shown by Figure 1.

C. *Realizing a CE and Informing Society*

Figure 6 shows some of the results that can be achieved by using all the techniques shown in Figure 5 that feed into the "Realizing the CE" box in that figure. It is of the utmost importance that the results we process metallurgists produce are understandable by all the stakeholders shown in Figure 1, while empowering global society to engage in the sustainability discussion. This should be the ultimate objective of the work we do, which helps to guide metallurgical systems to sustainability and to provide the license to operate.

The following sections provide a brief overview of what each of the pillars in Figure 5 could mean, coloring it in with the author's experience and work in academia and industry.

IV. PILLAR 1: SUSTAINABLE SYSTEMS AND SYSTEM MODELING

A. *Summary*

Product design has a crucial influence on the closure of the material cycles and the efficient use of resources. Acknowledging that products have complex "mineralogies" due to functionality reasons, fundamentally based system modeling is a key tool to evaluate the performance of the complex interlinked metal cycles referred to as the WoM. These are indispensable to provide information on the impact of consumer and technology behavior while keeping policy realistic and agile. These system models not only provide an important input to the economic dimension of sustainability but, perhaps more importantly, to the social dimension. Furthermore, these system models are the basis quantifying the RE of m-IoT and, hence, provide an important input to the environmental dimension of sustainability. Minerals processing plant simulation and optimization carry a wealth of knowledge that is applied with adaptation to the recycling field within the CE.

B. *m-IoT Network*

Multimetal flow networks or, in other words, the WoM[6,46] are complex and highly connected and not simulated easily due to the inherent complex nonlinear thermodynamics, kinetics, and transfer processes in metallurgical reactors. For this reason, the individual metal flows can never be considered separately as material flow analysis (MFA) does. The complex mixtures of metals and materials entering metallurgical reactors *via* minerals as well as products through their complex functional material combinations create these complexities in metallurgical processing.

A first attempt has been made to simulate this complexity in detail.[46] It was proven, for example, that it could be quite problematic to sustain the intricate interconnected metal cycle system if any metal production system is removed from the intricate WoM, *i.e.*, the primary and secondary metal production system. Of importance is also maintaining tacit process operational knowledge within the metallurgical industry—the knowledge that often makes it possible for operations to survive, run safely, be environmentally friendly, *etc*. This knowledge provides the content and substance of m-IoT; if the system is destroyed, for example, by legislation, the CE system will most likely collapse within a region. Obviously, this system will then migrate to places where full metallurgical processing infrastructures are available that cover the stakeholders and complexity shown in Figures 1 and 2.

The Metal Wheel[46] was developed to show in a simple visual way the intricacies of process metallurgy of

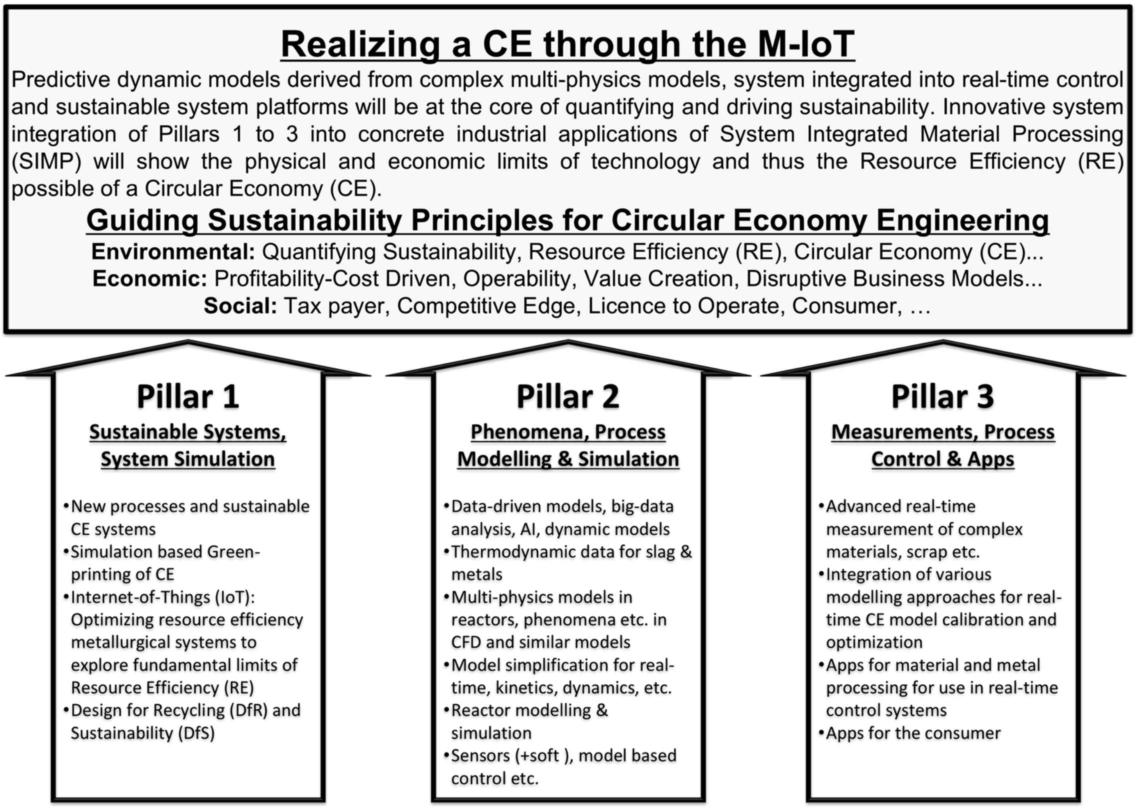

Fig. 5—Detail of each of the three pillars helps guides sustainable innovation.

primary ores to nonmetallurgists. These often tend to analyze metallurgical systems without including mineralogy or thermodynamics (thus entropy) in their MFA tools. The wheel shows that the minerals of the carrier commodity metals are unique mixes of inorganic compounds explained by geochemistry. Their treatment is governed by methodologies that fall under the umbrella of geometallurgy. This estimates which elements can be economically recovered, which are lost (the gangue), and which have to be collected and treated well due to their environmental impacts. The wheel was also intended to visualize the fact that their respective processing infrastructures are, in fact, the backbone of a CE. In other words, removing any one of the carrier metal infrastructures from the CE system will collapse it. It must be noted that the metallurgical infrastructure is a unique blend of process metallurgical technical as well as tacit knowledge that needs to be preserved lest it goes lost and, therefore, also the capability of the CE system to agilely adjust and evolve itself. Therefore, eliminating or disrupting the production of one element will have a ripple and knock-on effect over all connected carrier elements as well as all associated minor elements (often with considerable economic value) within the m-IoT.[6–11] It would be self-evident, therefore, that each metal and element within the WoM has a unique and delicate position, which all together will make the CE an economic reality.

Figure 8 visualizes this complex interconnected system though a Simulink[28] simulation model. It simulates the complex WoM that links the depth of metallurgical process engineering and reactor technology of the 10 linked metals. In a transparent scalable approach, the dynamics of process metallurgy have been linked to the tools that quantify the environmental performance of the global anthropogenic system of the flow of the depicted 10 metals.[46] Thus, all mutual dynamic and nonlinear effects are quantified and can be investigated based on the thermodynamically driven processes that occur in each reactor.

The complex interactions between the various reactors for the production of the various metals can only be produced with extensive industrial metallurgical process knowledge. Thus, the complex web of interactions can only be created in such a model if process metallurgy is known.

C. *Complexity of the CE*

Figure 8 may give the impression that the complexity of the CE system only lies in the connections and interactions for large-scale metallurgical processing systems. Figure 7 shows the next level of complexity; *i.e.*, EoL products and their produced scrap recyclates are rather complex mixtures.[4,11,46] Thus, to link the design of a product to recycling infrastructure, as depicted by Figure 1, is not easy. Linking these complex particles to metallurgical processing and optimizing the recovery of all materials and recycling these back into

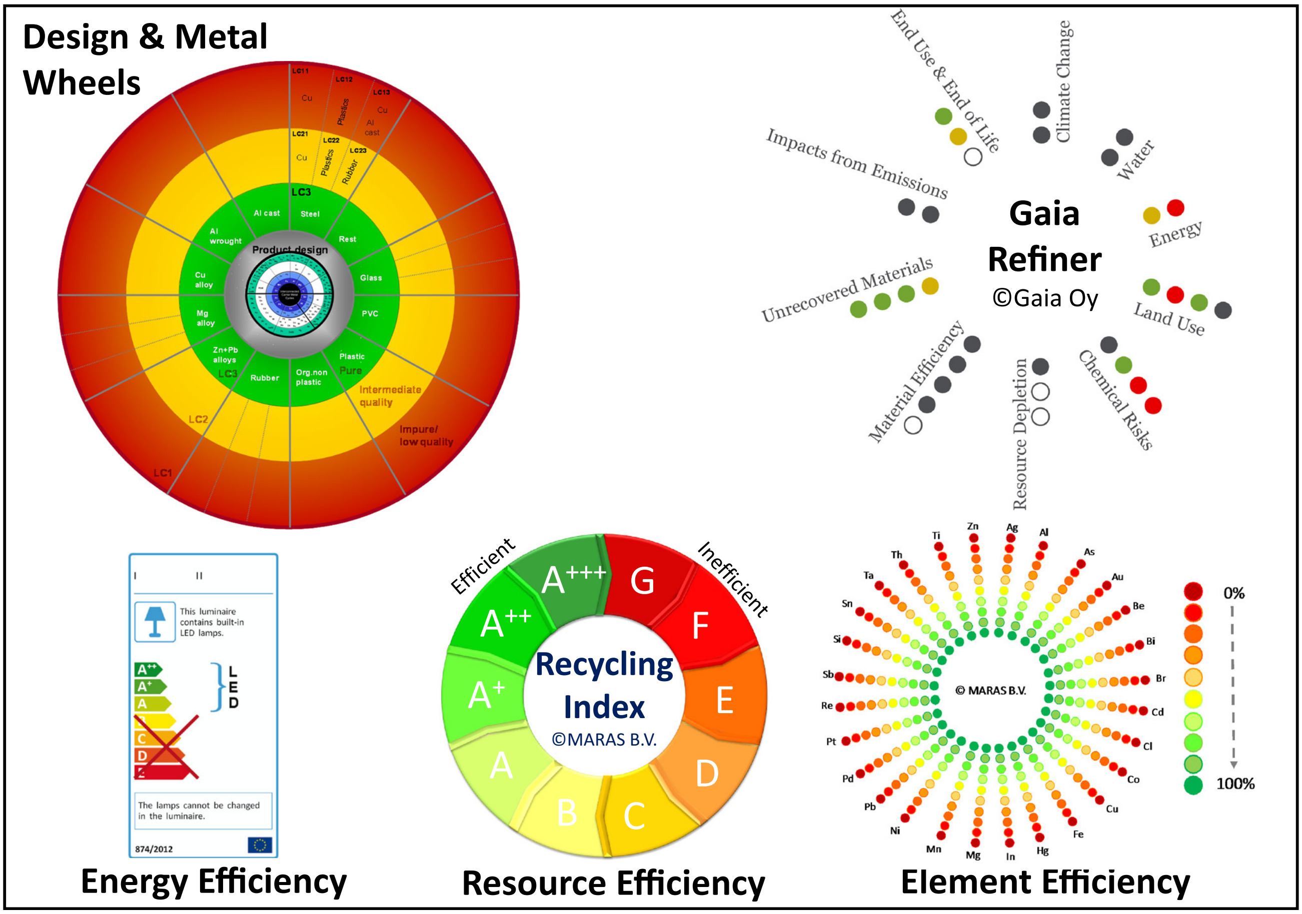

Fig. 6—M-IoT permits the optimization of both EE and RE, therefore providing the complete detail of iRE. Clockwise from top left: (i) the design wheel[12] for consumer products showing the effect of liberation classes (LCs) with reference to the Metal Wheel[46] (in the center), (ii) the Gaia Refiner[40,41] flower showing environmental impact relative to a baseline, and (iii) the accepted EE calculation[45] and the RI.[11]

the same products is the rather large challenge of a CE to limit the losses from the system.

There is the thinking that, by automatic sorting, improved recycling can be achieved. Considering Figure 7, it would be clear that, due to functional connections of materials, no sorting technology will ever be able to improve the RE of the recycling of these materials. Materials are together for functionality reasons, in many cases so intimately linked that only chemical separation is possible. Then thermodynamics comes into play dictating simply "You will win some elements and lose others, depending on the thermodynamics, technology, and economics."

D. *"Designing" Minerals—The Role of the Product Designer*

The geometallurgy of minerals is determined by the complexity of natural minerals. The metallurgical infrastructure for specific minerals has evolved and optimized itself around ore mineralogy for many years. Think of all the carrier metal infrastructures that presently supply metals, along with the associated technological and other critical as well as nonvaluable metals.

Product design and the product's functionality affect the behavior of complexly linked functional materials during shredding, cutting, or dismantling. Figure 7 shows different degrees of liberation, enveloping or similar; it is self-evident that the ultimate degree of metal and material recovery from these scrap particles is directly related to their complexity and the number of materials and metals that can be found in the large number of different scrap particles that originate from an EoL product. There is a chemical geochemical reason for minerals to be structured in the way they are; this is not the case for consumer "designer" minerals. Their complexity and functionality determines what metals and materials can be recovered and recycled back into the same products and what the losses from the recycling chain will be, as depicted by Figure 1 and Figure 2. In fact, the designer and the functionality thus determine the entropy state of the product and thus how much energy must be returned into the system to undo the entropy creation by the designer and product functionality.

Fig. 7—Minerals of recyclates in their different appearances as liberated (that can be sorted and recovered well) to unliberated fractions as well as various unliberated mixed fractions that produce poor quality recyclates. Sorting is thus not the only solution to all CE problems, neither is DfR.

To recover the metals from such complexity requires complexly linked metallurgical infrastructure that can recover as many as possible metals, as shown by Figure 7. This determines the RE of the CE system and also reveals what critical metallurgical infrastructure has to be available to act agilely to capture as many as possible metals and materials from this complex WoM. Therefore, it is key that the metallurgical infrastructure must continue to develop and evolve in order to capture as many as possible materials and metals in the WoM, playing its key enabling role in the CE system.

E. *Minerals Processing and Process Metallurgy—The Roots of CE System Models*

Commercial CE systems, as shown by Figures 1, 2 and 7, never create pure material streams from the various materials from end-of-life vehicles and EoL consumer goods. It would be self-evident that 100 pct recycling rates are never achieved during physical separation nor 100 pct metal recovery during metallurgical processing. These facts are simply dictated by separation physics, thermodynamics, kinetics, stochastic processes, measurements, sampling and sample analysis distributions, transfer processes, technology, entropy creation, product distributions, types, *etc*. These aspects all affect the quality of the recycling streams, as depicted by Figures 1, 2, and 7, which determine the mineral classes (thus the combination of materials in the product and thus in the scrap), particle size distribution (of scrap and particles), and degree of liberation, as shown by Figure 7. These parameters affect the physical separation efficiency, metallurgy, and energy recovery, which all as a result determine the quality and economic value of the recycling products in the CE system.

It was explained earlier that design determines the quality of recyclates and thus the ultimate recycling rate of a product, as shown by Figure 2. It will be a key innovation to have recycling tools available that are linked *via* CAE and CAD software tools that can predict recyclability of a product during design. All materials and metals in the product have to be accounted for when estimating the RI of products. At the same time, the social and environmental value of the materials applied in the product are revealed, thus informing and empowering the consumer to make decisions when purchasing these goods.

Therefore, it is a key innovation for a CE to simulate the complete system by dedicated tools that include minerals processing and metallurgical depth.[13,26,32] These quantify RE and thus estimate the limits of the CE system and thus of the CE paradigm. This demands a deep understanding of first-principles knowledge of recycling processes as alluded to previously. It requires continuous further innovation in pyro- and hydrometallurgical systems and their agility so that it can deal with the ever-increasing complexity of modern consumer products. The mentioned tools include this depth.

F. *Optimization and Quantification of the CE System*

Predicting the RI of EoL products during the design stage requires the simulation of recycling on a fundamental basis, as noted previously. Figure 7 shows that if RI values are of any value, their underlying theory must consider and embrace the following: (i) material composition, *i.e.*, both physical and chemical; (ii) the calorific values of the (intermediate) recycling streams based on their composition and mineralogy; (iii) material and mineral classes; (iv) particle size classes; (v) liberation and agglomeration classes of scrap (Figure 7);[39–41] (vi) the economic value of intermediate streams based on metal values;[9,11] (vii) separation physics as well as metallurgical process thermodynamics;[9,11] (viii) losses and emissions and their mineralogy;[11] (ix) harmonization of processing infrastructure with changing product design;[4,9] and (x) distributed and dynamic properties of functional materials in present product designs simultaneously anticipating future designs.[47–49] Figure 9 provides a detailed flow sheet of an example of a recycling optimization model,[39] from which it is clear that the complete flow sheet of recycling is always considered. Thus, physical separation and process metallurgy are always linked. Most recycling flow sheets in environmental analysis do not consider or simplify this so important aspect.

Optimization has evolved considerably over the years with various tools, more recently incorporating surrogate-assisted evolutionary computation.[18–22,28] The progression of system optimization modeling started for the author with minerals processing,[13] incorporating industrial experience in process control, metallurgical reactor design and simulation, and minerals processing modeling and plant optimization. The following points plot this path.

(1) With the knowledge of minerals processing and from observation of particles created in recycling systems (Figures 1, 2, and 7), we can define the fundamental basis of the CE systems in terms of (i) mineral classes, (ii) particle size classes, (iii) liberation classes (LCs), (iv) agglomeration classes, (v) the link between these, and (vi) the definition of the minerals for a consumer product through a sequence of publications.[4,15,39]

(2) Through this, the dynamic nature of CE systems could be investigated, showing the effect of time delays in the system on recycling rate as well as highly distributed properties.[48] Subsequently, we could quantify the fundamental limits of RE in relationship to product design.[15]

(3) Liberation, physical, and chemical separations are key to the production of pure recyclates within the recycling system.[49]

(4) Furthermore, LCA methodology was developed to evaluate the environmental impact of the performance of larger systems and linked to HSC Sim.[26]

(5) The effect of particle size reduction and liberation on the recycling rate of products was investigated theoretically and industrially[12,15] to show what the key cause was for losses in the recycling system and, hence, the reason for low recycling rates and the key limitation and challenge for a CE system. Also, linking design and liberation of materials during shredding to the recycling models made it possible to estimate recycling rates as a function of product design.

(6) In order to calibrate these models, we conducted large industrial scale recycling trials to estimate the recycling rates for products including what recovery process metallurgy delivers.[6,9]

(7) Extractive metallurgy designs are always underpinned by detailed process flowsheeting and simulation for evaluating alternative solutions. However, most flow sheets in environmental analysis do not consider or simplify the preceding detail. We considered these aspects, for example, in detail for lead,[43,47,50] zinc,[43,47,50] and copper flow sheets,[11,42] including their optimization and industrial understanding.

(8) The quality of the recyclate streams ultimately determines in which processing steps of the complex flow sheet (Figure 9)[39] these materials can be economically processed to metals, high-quality materials, or energy.

(9) To assist the product designer, the Design Wheel[7,12] (Figure 6) was developed to reflect the (in)compatibility of material combinations in the recyclates and their effect on the RI. The colors in the wheel help to visualize the imperfect liberation or separation. This compatibility is based on the material combination matrix,[6] which in turn is based on the thermodynamics and kinetics of metallurgical processing. This explains simply why, for example, copper and gold connected to steel will dissolve in steel, but since copper and gold are more noble than steel, these cannot be removed from steel during steelmaking.

In summary, Figures 1, 2, and 8 implicitly depict how product design combines metals and materials originating from the primary and secondary sources into a complex multimaterial functionality. Figure 9 reflects the knowledge and modeling detail that is captured by the developed recycling optimization tools and provides feedback to the designer on desired and undesired material combinations in the design. The Design Wheel[12] and Metal Wheel[46] shown in Figure 6 act as a preliminary DfR tool helping the product designer to understand the complexities of physical separation as well as metallurgy. Thus, the Metal Wheel[46] explains why, if certain fractions are liberated, they can be well recycled or lost significantly.

G. *Linking Product Design to Recycling*

Figure 9 depicts a system for EoL products (*e.g.*, vehicles passing through a shredder) recycling and a complex optimization model for doing so. Figure 1, 2, 6, and 7 depict recyclate particles after shredding/cutting/sorting, the complexity of which determines their recyclability, among others, due their quality and resulting economic value.[4,9] The economic value of each material and metal, determined by both the London Metal Exchange (LME) price and the mass of each metal and material in the product (and thus in scrap particles), is a key driver in realizing the CE system. Undesired material combinations and contaminations diminish economic value (if exceeding permitted concentrations, alloy specifications, *etc*.) and hence recyclability, as these could potentially dissolve in metals, appear in flue dusts, and report to slag, slimes, residues, sludges, *etc*. Simple tools such as the metal compatibility tables as well as the Metal Wheel were developed in the late 1990s and early 2000s[6,7,9] for design engineers to visualize these complexities. Furthermore, product complexity creates complex residue streams or undesired possibly harmful emissions that may not be recoverable in the current system and process metallurgical infrastructure. As a consequence, these residues will have to be stored in well-contained ponds so as to be possibly recovered in the future when the economics are better, which may also imply that uses may have been found for these presently invaluable elements.

Simulation[11] and optimization models,[39] of which the flow sheet depicted by Figure 9 is an example, are imperative to evaluate all the complex interactions that determine economic viability and environmental impact. However, these models are often too complex to link to CAD directly. For this reason, simpler approaches were developed, *e.g.*, fuzzy logic models,[12] that learn and map these complex models from the numerical results of the recycling simulation and optimization models. As for the simulation models, these fuzzy logic models can be linked to CAE and CAD software, and they can also be integrated into LCA tools[11,26] to help design RE efficient products. A key innovation, therefore, is to link product design to simulation and to environmental impact to ensure the RE of the CE system can be quantified. This helps minimize the loss of valuable materials and metals from the CE system as well as prevents the decrease of both qualities of recyclates and recycling rates of products.

H. *Theoretical Basis for the m-IoT*

The previous sections briefly mention what is discussed in the various publications cited, providing an overview of some fundamental aspects required for the m-IoT[9–11] and, hence, for the metrics to measure the social, economic, and environmental sustainability of our consumer society. Figures 8 and 9 summarize this, *i.e*., application of m-IoT, in which first-principles simulation models link metal and material choices in product design to recycling and interconnected material cycles, at the same time quantifying the environmental impact *via* LCA[26,78–80] as well as exergy,[26,81] as shown by Figure 10.[10,11] This provides fundamental knowledge and quantifies the ecological value of materials in our society. This would then constitute the true objective of a CE in the present industrialized society, *i.e*., linking metal production to process and product design as well as product recycling. This is a key issue in controlling the anthropogenic metal cycle: limiting the negative interaction with the environment is minimized; in other words, RE is maximized. Rigorous modeling of CE systems reveals the limits of CE systems on a first-principles basis, which is the key message of this article. M-IoT is required for realizing CE, which implies that a metallurgical infrastructure is a crucial part. It is the process engineer's task also to demonstrate not only techno-economic viability but also system sustainability in all three dimensions, as shown in Figure 4.

V. PILLAR 2—PHENOMENA, PROCESS MODELING, AND SIMULATION

A. *Summary*

Closing the material and metal cycle is not possible without a thorough knowledge of the technology (and its theory) that creates and recycles the metals and materials used in consumer products. Not only does this require a good fundamental description and understanding of the technology, but it also requires sufficient measured data to calibrate models and also to predict environmental performance. This section shows that the principles of process engineering have an important and necessary role to play within any sustainability discussion. It is also crucial to understand the bigger system in which this technology is residing of which process control is a fundamental ingredient. High-temperature process reactors will be the focus of the discussion, since it is conjectured that these are crucial for closure of the material cycle. Process metallurgical reactors facilitate sustainability in metals processing and are key to a CE paradigm; in fact, metallurgical reactors and metallurgy are the true "closers" of the loops in the CE system.

B. *Calibration of Models, Data Driven Modeling—Big-Data and System Analysis*

EoL consumer goods are a valuable resource of metals. Processing these is key to recycling and "closing" of the metal and material cycles, contributing to the sustainability of the CE system. Rapidly changing metal combinations in consumer products challenge the current boundaries of thermodynamics and kinetics and their use to recover these metals from postconsumer products in metallurgical reactors, as shown by Figure 8. Figure 8 shows that the distribution behavior of key elements has a vital impact on where these metals report in the CE system either as products or residues. As explained, optimizing the CE system requires detailed knowledge and control of process metallurgical reactors. Calibrating process models requires detailed sampling and real-time analysis of data. Classical sampling theory and statistically based data reconciliation play an extremely important part when collecting data, closing mass balances over unit operations, plants, and systems, as depicted by Figures 1, 2, and 8 through 10. The reconciled data may then be used to calibrate the simulation, optimization, and dynamic models.[51–55,57–59] The key is linking industrial

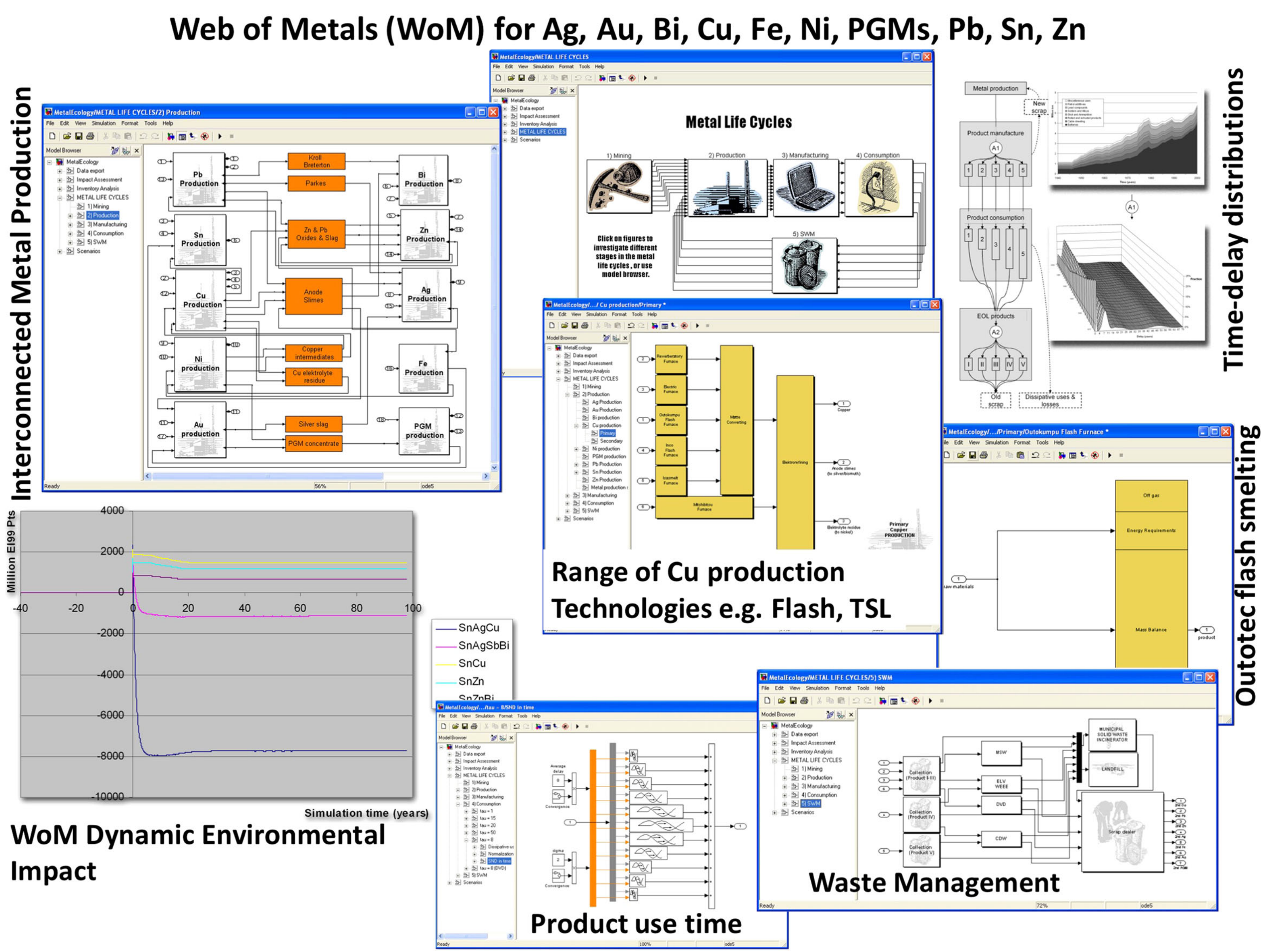

Fig. 8—Dynamic modeling of the WoM of the 10 shown metals with Simulink®.[28] The model links individual metallurgical reactors that process different EoL products and their materials with the calculation of the dynamic environmental impact for the WoM of 10 metals, while considering the distributed life times of all products.

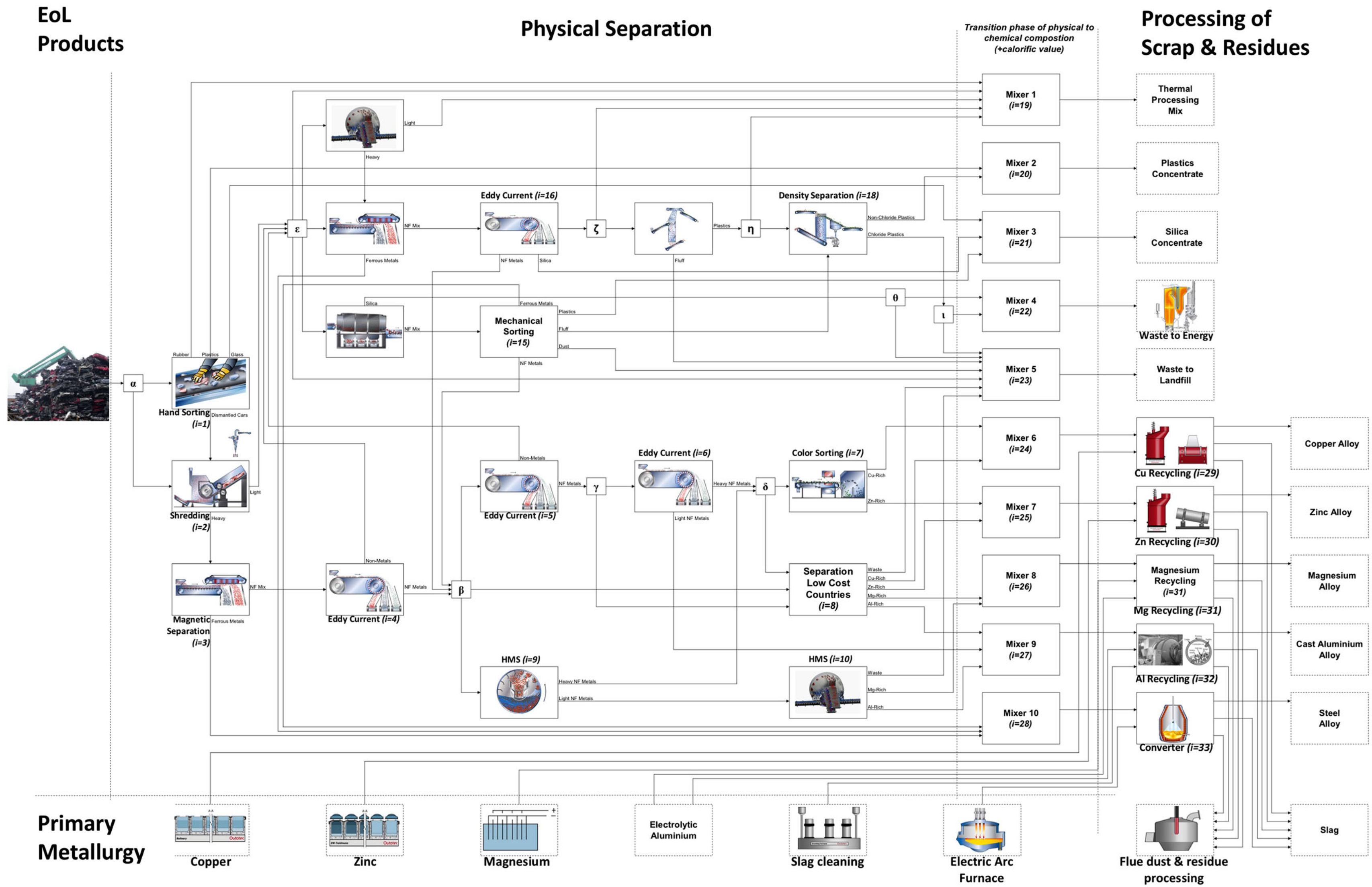

Fig. 9—A flow sheet for an optimization model[39] for a detailed recycling system showing the routing possible for EoL materials, scrap, and products, which can be calculated as a function of different objective functions (*e.g.*, economic, recovery, or environmental impacts). This shows the importance of considering and building an agile system to maximize RE (programmed in AMPL.[22])

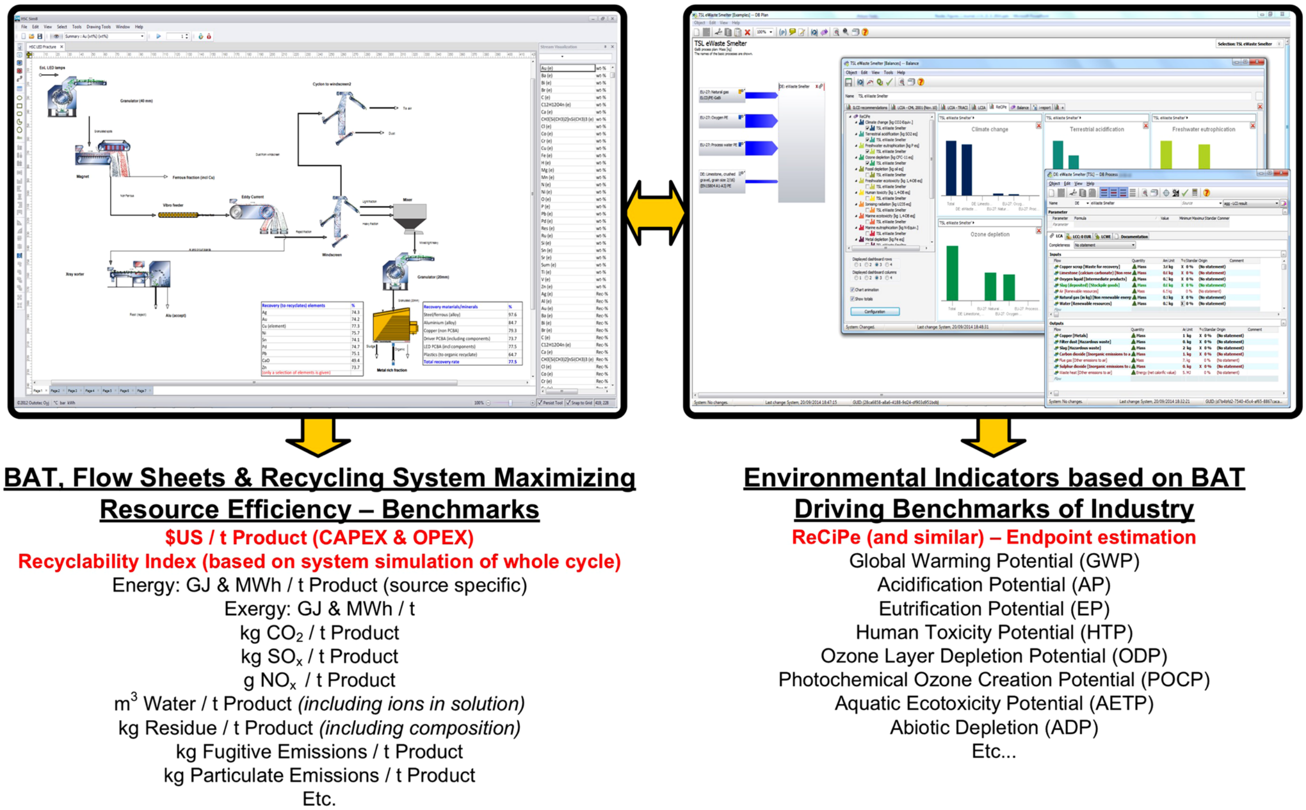

Fig. 10—Linking process design and large system simulation to environmental impact analysis.[9–11]

compositional data of the EoL products, their separation efficiency in separation processes, their liberation, and their quality (or grade) to their behavior in process metallurgical reactors.

System optimization models, if they have any value, require detailed industrial calibration data on the reactor and unit operation level. If the models can be calibrated by industrial data, these obviously provide a theoretical basis for detailed collection of process data as well as product data defining them in detailed mineralogical granularity. The preferred basis for data collection applies data reconciliation, and the corresponding sample and sampling statistics, when auditing an industrial plant, are underpinned by sampling theory.[6] In addition, the simulation models support system optimization models on the basis of rigorous mass and energy balances.

Reducing large bodies of real-time and other data from the reactor to the system level requires significant data reduction techniques that then can be applied to calibrate simulation models and flow sheets. Numerous software tools exist[51–54] that can perform the tasks of data acquisition and reconciliation and then use these reconciled data to optimize processes, furnaces, and complete systems. Platforms such as the PI System from OSIsoft[33] have gone a long way toward harmonizing real-time data acquisition with complex system models to optimize complete plants. This requires that data have a unified format that is scalable, *i.e.*, that permits the mineralogy of ores, minerals, consumer goods, *etc.* to be quantified in terms of compositional and material associations (*i.e.*, geometallurgy), and linked to the thermodynamic data formats of process simulators. Furthermore, for the data to be usable in simulation models that define the system, as depicted by Figures 1 and 2, these data should have the same time stamp inclusive of time delays, as reflected by Figure 3. If these data from the geological and urban mines (Figure 1) are compatible, they can be usefully linked and used to optimize metallurgical processing systems.

Metallurgical reactors, such as the top submerged lance (TSL),[42,43,60] can be rather complex and difficult to model due to issues with understanding the true feed compositions and mineralogy of scrap and residues, measuring representative data of the temperature of phases, sampling of materials inside high-temperature reactors, the distributed nature of conditions within the reactors, the poor definition of feeds, in particular, of residues and scrap entering furnaces, the poor mixing in some reactor types, *etc.* Modern analytical techniques provide a manner to estimate and also provide insights into these reactor types and systems. The author has been involved in this for many years, as the following examples show.

(1) Use reconciled data for TSL,[61] submerged arc (Si, FeSi, FeCr, FeMn, CaC_2),[59,62] salt slag aluminum recycling,[63] chemical waste incineration, and blast furnaces (among others) to create dynamic models linked to thermodynamics (captured in neural net functions) to predict metal recovery, heat loss, matte

grades, *etc*. as well as for environmental impact assessment.

(2) The use of AI and big-data analysis techniques for the modeling of ill-defined metallurgical reactors has been ongoing since the early 1990s,[58,59] and various platforms have evolved that apply these practices.[51,52,55] These techniques provide valuable insights into technology and permits to extend help in their optimization when using well-conditioned real-time data; *e.g*., neural net estimation and capture of thermodynamics relationships data were published for the first time in this journal in 1992,[56] as were the data on approximating kinetics with neural nets in 1993,[57,58,64] followed by various applications such as reactor diagnosis and optimization, as depicted by Figure 11.

C. *Metallurgical Reactors—Closers of the Metal and Material Cycles*

Metallurgical reactors play a key role in closing the material cycle.[4,10,11] For these reactors to optimally do this, a thorough knowledge of metallurgical process engineering and technology as well as the associated knowledge of thermodynamics is required. At the same time, process control is a key to achieving optimal reactor performance, minimal energy consumption, minimal residue creation, and maximal production of metal.

If one considers the flow sheet (Figure 9) for the recycle of EoL products, it is clear that metallurgy plays a significant role, also to an extent do end-of-pipe solutions to waste abatement. Therefore, in order to be able to produce optimal system models for the recycling chain, a detailed process and fundamental knowledge of metal processing are required. To this end, a large body of work has been completed by numerous authors and published, for example, in this journal. Experimentally measured thermodynamic and kinetic data are and have been systematically collected, formalized, translated, and made accessible in numerous innovative software tools[34–38,65–67] that visualize and use the created experimental data to assist in optimizing process metallurgical reactors and systems. These tools can then be used after rigorous industrial calibration and verification to visualize and understand phenomena in furnaces, as shown for example by Figure 12.

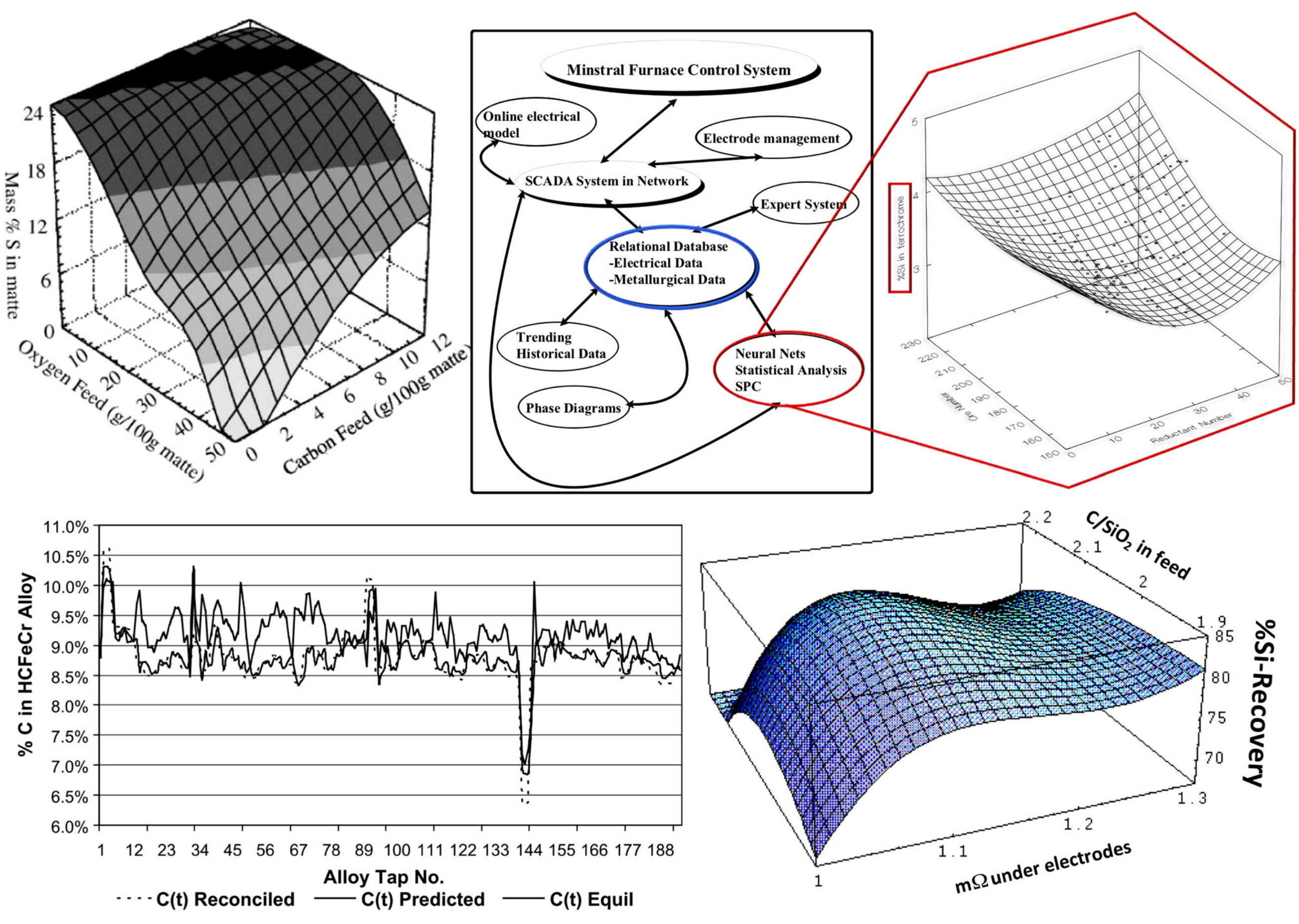

Fig. 11—Big-data analysis of ill-defined metallurgical systems (clockwise from top left): (i) *top left* dynamic modeling linking data driven approaches with thermodynamics;[61] (ii) *top right* intelligent control of submerged arc furnaces (SAFs) highlighting the central role of a database with reconciled data that link mine, ore, and reductant characterization numbers (geometallurgy based), mineral to metal product;[59] (iii) *bottom left* dynamic modeling of FeCr production and product quality;[62] and (iv) *bottom right* optimizing silicon metal recovery in a silicon SAF on the basis of various independent operational parameters.[59]

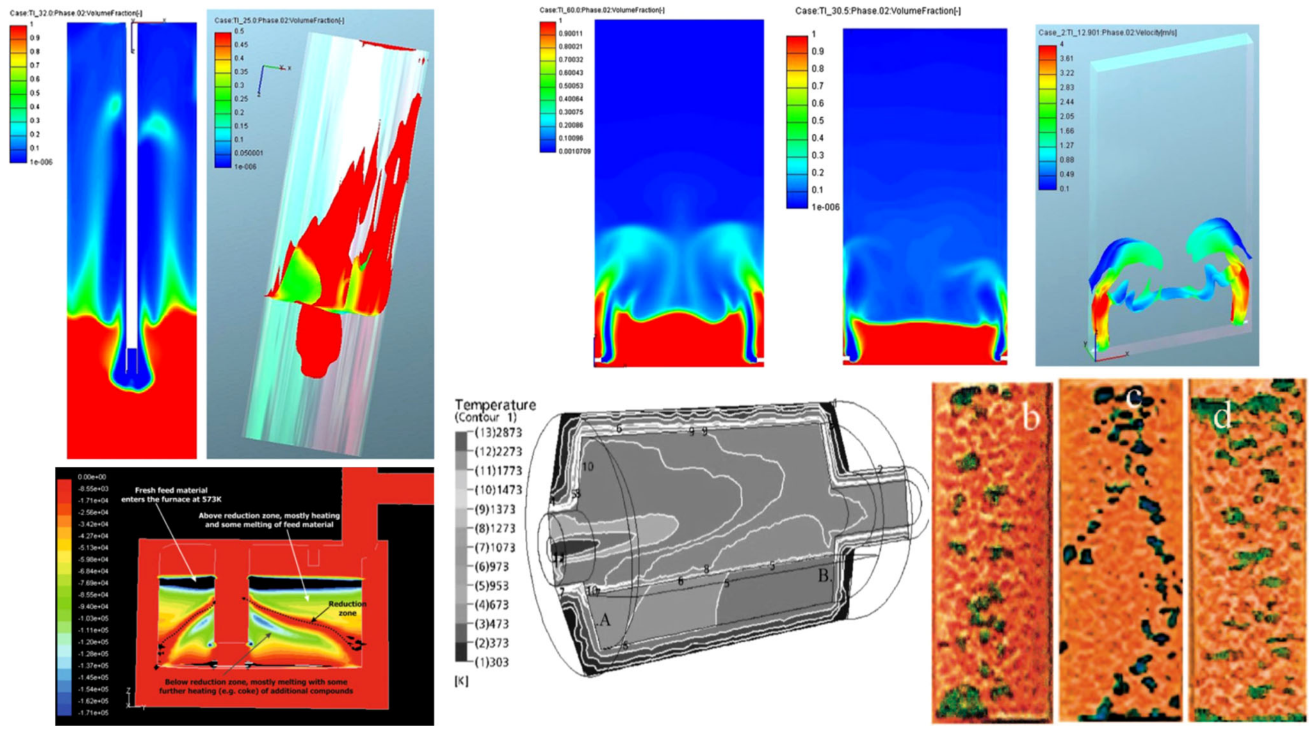

Fig. 12—Computational fluid dynamic analysis of TSL, slag fuming, submerged arc, and rotary aluminum recycling furnaces, respectively (clockwise from top left): (i) TSL smelting,[70] (ii) zinc box fumer,[71] (iii) phosphorous SAF smelting,[72] (iv) rotary salt slag furnace for aluminum scrap remelting,[63] and (v) X-ray tomography images of slag and pig iron flow through the packed coke bed of blast furnaces.[73]

D. *Understanding Scrap Particles in Their Full Three-Dimensional Multimaterial Complexity*

Particles play an important part in recycling systems.[9–13] Particle behavior and, hence, controlling their destinations during physical separation are of extreme importance for realizing a CE to maximize RE. Equally important is the behavior of particles and their interaction with gaseous, aqueous, and molten phases in metallurgical reactors,[63,73] aspects that are simulated by DEM[68] in combination with CFD methods—various examples exist in metallurgy including for blast furnaces, fluidized bed reactors, and rotary kilns, to mention but a few.[69] This is an important field of development that will further enhance the understanding and maximization of RE within the CE system. CAE tools, such as modeFRONTIER,[67] already go a long way toward integrating, for example, flowsheeting tools, CAD, DEM, and CFD under the umbrella of CAE through which optimization of reactors, products, and systems, for example, can be done. These types of platforms will increasingly be used, which also include LCA environmental indicators in objective functions for the optimization of systems.

E. *Value of These Models and Approaches?*

With all the detail of the reactor technology discussed previously, as well as a thorough understanding of the thermodynamics, kinetics, and technology of processing including all the stakeholders reflected by Figure 15, it should be possible to create sufficiently accurate system models that predict the recycling performance of the complete CE system. However, all these methods are as good as their calibration and comparison with the real world, and these thus can be used to optimize reactors, processes, and systems. Often impressive colorful pictures and MFA results are produced through the use of these methods, though it is still rather challenging to create suitable DfR and DfS tools as well as quantification of RE that reflect reality well. If all the preceding information is known and integrated within the models with a clear interaction between model builders and industrial application, significant improvements will be achieved.

VI. PILLAR—MEASUREMENT, PROCESS CONTROL, AND APPS

A. *Summary*

Quantification of the RE of the CE system is key in driving its innovation and its success. The required digitalization to link the WoM together into the m-IoT is a unique opportunity of the metallurgical processing industry to lead the IoT paradigm for a CE. It has been shown that various simulation techniques exist connecting product design to process metallurgy, but these still need work. This section will discuss this aspect and also suggest developing easy-to-use computer applications (apps for various IT platforms) that can be used by the general public to access RE information easily to assess and understand its personal footprint.

B. *Estimating All the Properties of Complex Materials in Real Time*

Process control and system dynamics are key aspects of understanding CE systems. The previous sections discuss various dynamic modeling methods, both through simulation and *via* data-driven approaches. In the context of CE, this section will elaborate briefly on some key aspects that are of importance to realizing and quantifying the m-IoT and, hence, delivering the detail and platform from which innovative CE business models can be developed.

The previous sections have also shown the methodologies and tools that are available to model and simulate physical recycling systems. In order to do this well, real-time analysis of scrap is required, which simultaneously records the various particle properties such as particle shape, size, composition, mineralogy, conductivity, density, color, odor, magnetic susceptibility, liberation, and agglomeration. These properties are necessary to capture the detail required by separation models for the unit operation in recycling systems, as shown, for example, in Figure 9. A range of particles are depicted in Figure 13, the properties of which have been included in the simulation models discussed previously.

Physical separation systems for sorting particles through real-time analysis have already evolved significantly.[74] Usually, these industrial systems act only on one property and sort accordingly, *e.g.*, by color, near infrared, magnetic, or eddy. The innovation in the future will be to use multisensors and in real-time feed information to calibrate simulation models that track particles[8,11,26] through complete recycling flow sheets. Proxy measurements done with three-dimensional (3-D) X-ray tomography[75] as well as mineral liberation analysis (MLA)[76,77] will help to link multimaterial real-time measurements to the calibration of recycling and system simulation models. This will capture the mineralogies of ores as well as scrap, hence enabling the linking of all the stakeholders in Figure 1[4,9,10] on a fundamental basis.

Figure 14 shows the type of platform[26] that is required to perform the real-time measurement and the tools necessary to analyze, simulate, and optimize the recycling as well as implicitly the CE system. The big-data and other data analyses techniques mentioned previously are all required to calibrate simulation models which then enables real-time plant and system optimization. As a result, optimal recyclate grades and recoveries can be achieved, tuned, and optimized according to market conditions as well as to the feed of EoL products, materials, residues, and goods that are constantly changing through societal and consumer behavior.

The key innovation that this brings is that it links recycling to product design *via* a detailed analysis and simulation to the prediction of metal recovery during metallurgical processing. This subsequently permits a detailed calculation of RE and thus the loss of materials, elements, alloys, *etc*. to streams of low economic value. Included is all the statistical information that documents standard deviations, averages, *etc*. all as a function of time.

It was proposed for the optimization of flotation plants[13] that a flexible minerals processing plant structure could help to optimize grade and recovery. This means that the processing plant can in an agile manner adapt to changing feed conditions and ore grades, not only by changing flotation and grinding

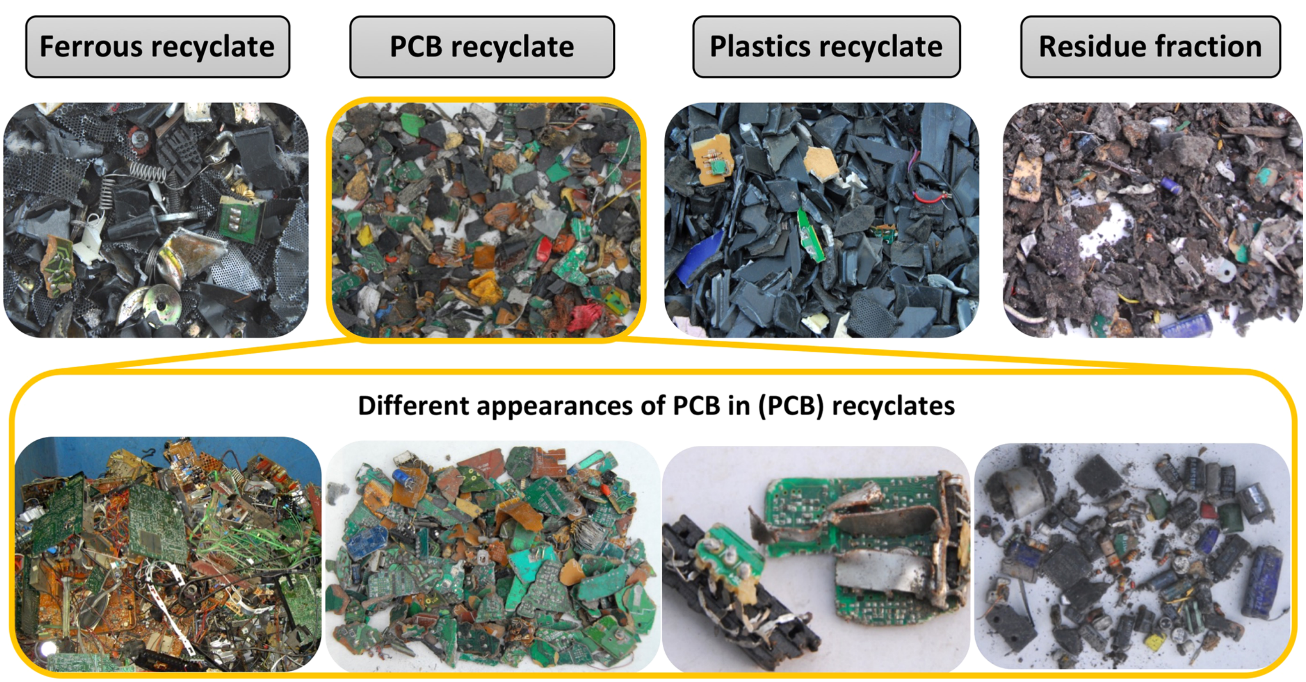

Fig. 13—Some examples of scrap (top row) and the wide resolution possible from printed circuit board (a fraction of waste electric and electronic equipment (WEEE)) scrap (bottom row).

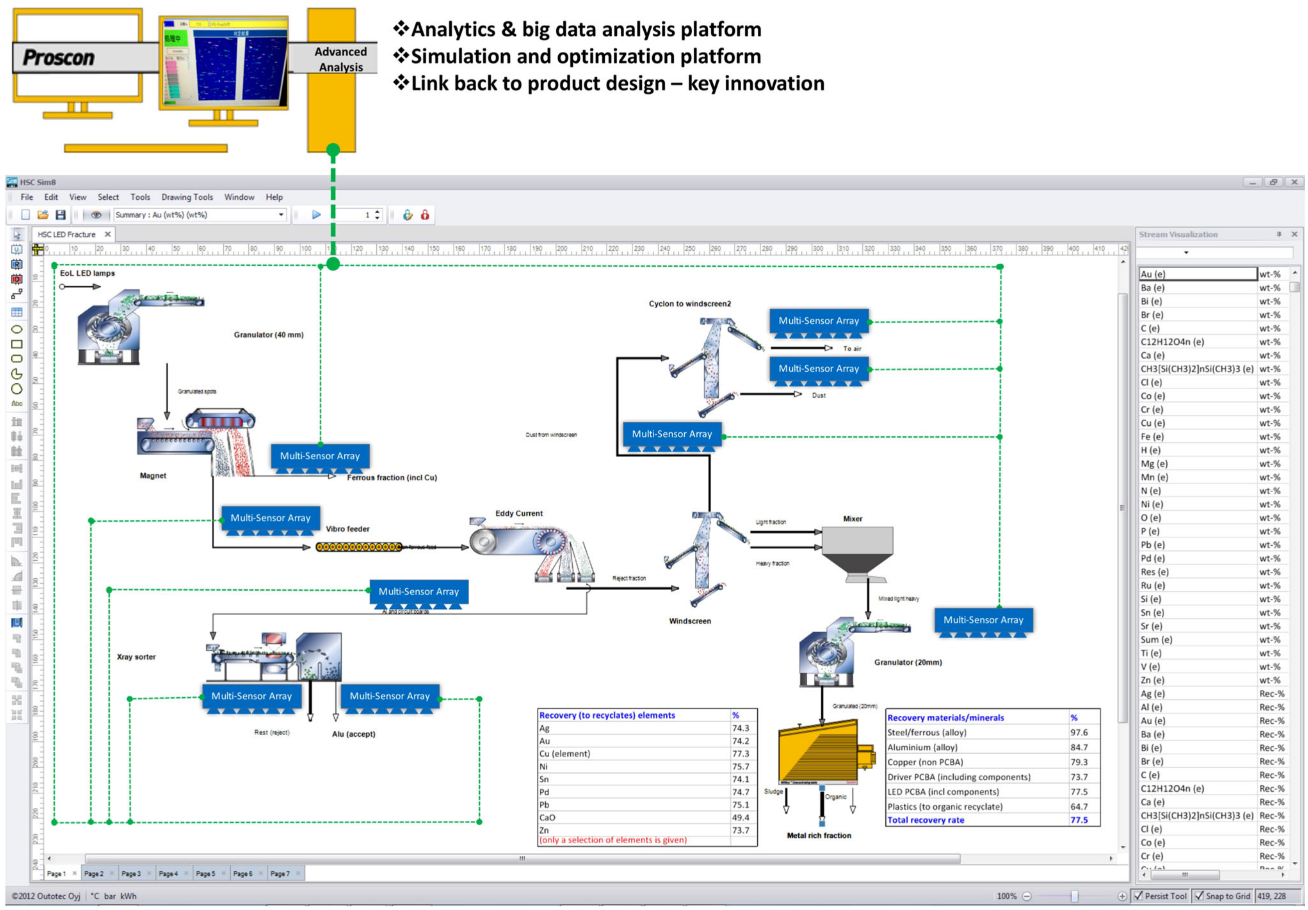

Fig. 14—Measuring the properties of particles within a physical separation plant with multisensor arrays, parameterizing simulation, and optimization models,[9,11,13,39] and subsequently simulating and optimizing the recovery of elements as well as materials and linking the outcomes back to the CAD models of product design.[15] Proxy measurements using tools such as MLA, 3-D X-Ray tomography, and microprobe will augment the real-time measurements.

conditions, but also through rerouting streams to different unit operations. This is also implicitly what the optimization of complete recycling systems suggests, as depicted by the optimization models reflected by Figure 9.[39] A key innovation of the future, similar to what was done for flotation, is to link optimization models with simulation models to maximize RE by optimal routing of EoL products, scrap, materials, residues, *etc*. to appropriate metal production and refining infrastructure, as shown by Figure 9.

C. *Informing and Empowering Society*

Metallurgical systems are complex and simulation models can become rather complicated and detailed and in some cases so detailed that they have no practical value nor can they be easily calibrated and tuned with real-time data. Obviously, these are not easy to use and even more challenging for society to understand, but these define the basis of RE and cannot be simplified to produce trivial academic solutions.

It is crucial for the metallurgical industry to picture its complexity in simple-to-understand visualizations.[11,82] Figure 6 shows such a visualization that could inform the consumer of the recyclability of products showing the recovery of all elements (weight averaged) as a RI for the complete cycle shown by Figure 1. It is also useful for the product designer to visualize the effect of redesigns of a product and their effect on recycling, providing a rigorous basis for DfR, as often the complexity of metallurgy is not fully understood by everyone.

Furthermore, if environmental impact modeling and simulation are going to have technological meaning, one has to include an extremely detailed and fundamental understanding of the complete material cycle, its technology, and the manufacturing industry. This requires that all stakeholders work closely together to realize this, as suggested by Figures 1 and 15. Above all, it requires a detailed understanding of all the technology, thermodynamics, and physics of all the reactors in the m-IoT (as shown by Figure 8), economics, policy, and legislation of the system depicted by Figure 1 and integrates this into CAD and CAE tools.

Presently, the CE discussion is often still rather general and neglects the detailed discussion of true losses from the system due to complexity. The document by the MacArthur Foundation[83] is such an example, in which figures similar to Figure 15 are depicted but do not precisely detail all the losses shown in Figure 15,

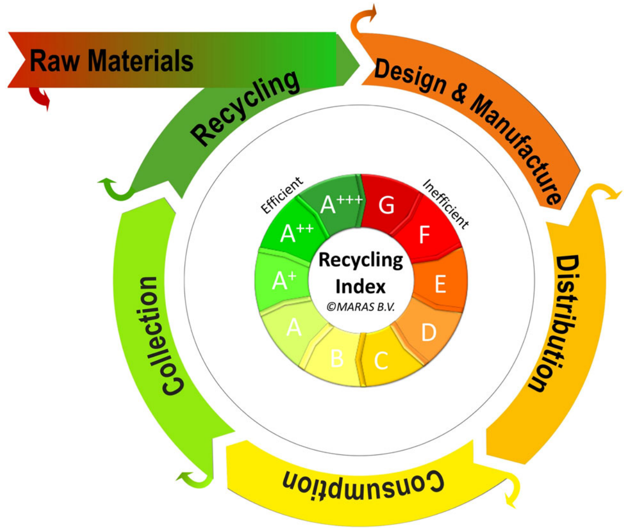

Fig. 15—Maximizing the RE of the CE system and its stakeholders, therefore driving the losses of each stakeholder as low as possible by decreasing all losses from the system. This acknowledges the second law of thermodynamics in addition to what is economically and technically possible (Fig. 3).[1,43]

therefore risking oversimplification of the benefits of a CE. The losses, not clearly shown and discussed by the MacArthur Foundation,[83] will all have to be managed well within techno-economic boundaries to maximize the RE of a CE for society.

There are various organizations that are already advancing the CE field by quantifying sustainability while also supporting business development, *e.g.*, the World Business Council for Sustainable Development,[85] the Water Footprint Network,[86] the Global Footprint Network,[87] and the United Nations Environmental Programme's International Resource Panel.[88] These actions are truly commendable, and these organizations are doing the "right thing" by informing RE. Best available technique processing technology for metallurgy plays a key role in closing the loop,[89] as shown by Figure 1, by applying technologies such as those depicted in Figure 16.[90] It is important that these technologies be positioned optimally in the system, in metallurgical corporations, and in the policy landscape in order to provide their greatest RE impact.

VII. SUMMARY—THE m-IoT

A. *Summary*

Engineering has always had a strong societal role and impact. The present global situation requires more than ever a leading role from engineers by the application of their unique design skills and engineering approach to the creation of sustainable technologies and systems; or, on the other hand, to provide the tools to analyze systems to reveal the limits of the CE and what technology cannot provide and perhaps only human behavior can. Their strong practical and techno-economic based problem solving abilities are a key ingredient of this analysis. Legislation plays an important role in recycling, environmental control, *etc*., contributing to rendering our future more sustainable. Engineers can contribute significantly to this debate, enhancing the (fundamental) quality of the legislation, identifying its flaws, and subsequently assisting in the creation of legislation that inherently contributes to and enhances sustainability.

B. *Criticality of the Metallurgical Processing Infrastructure*

Various approaches to questions of crucial importance to the quantification of RE of the CE system have been discussed in this article. Various industries are taking these approaches on board to ensure among others that sustainability criteria are met and that industries are good global citizens.[11] These approaches, however, also show the challenges and limitations and pose difficult and complex questions regarding the achievability of a CE. With the advanced tools alluded to in this article and industrial calibration data, however, useful simulation and business models can be developed; therefore, the potential and risks of a CE should be explored and quantified to minimize the losses shown in Figures 1 and 15. The criticality of maintaining a metallurgical processing infrastructure is key to keeping the WoM agile.

The importance of deep understanding (both tacit and theoretical) of the process metallurgical technology within the CE system is highlighted as a key enabler. It is crucial for engineers to be part of this legislative, policy, and political discussion, bringing into it the rigorous process of the engineering and technological method. A further objective is for engineers to keep society informed so that clarity exists and can be communicated on a rigorous techno-economic basis. Thus, process metallurgists play an important role in this public dialogue. However, process metallurgy should visualize its results in a manner that educates the public; therefore, metallurgists should be playing a leading role in this dialogue, as reflected by Figure 6.

It is clear that recycling plays a crucial part in the complete resource cycle of a CE, as it increases RE through high-tech sorting and metallurgy (Figure 8). As recycling technology comes of age, it will move in general to a more sophisticated sorting technology and digitalization, as depicted by Figure 14. As computing power increases and sensors become more sophisticated, so will the ability to deal with extremely large bodies of data, which, for example, will characterize the multitude of particles in scrap and all their material properties. Complexity, however, can also mitigate the possibilities of these developments.

C. *Circular Economy Corporation*

It goes without saying that corporations that understand the complete material and metal cycle will remain viable in the future and help to drive the sustainability path and also show the importance of the metallurgical

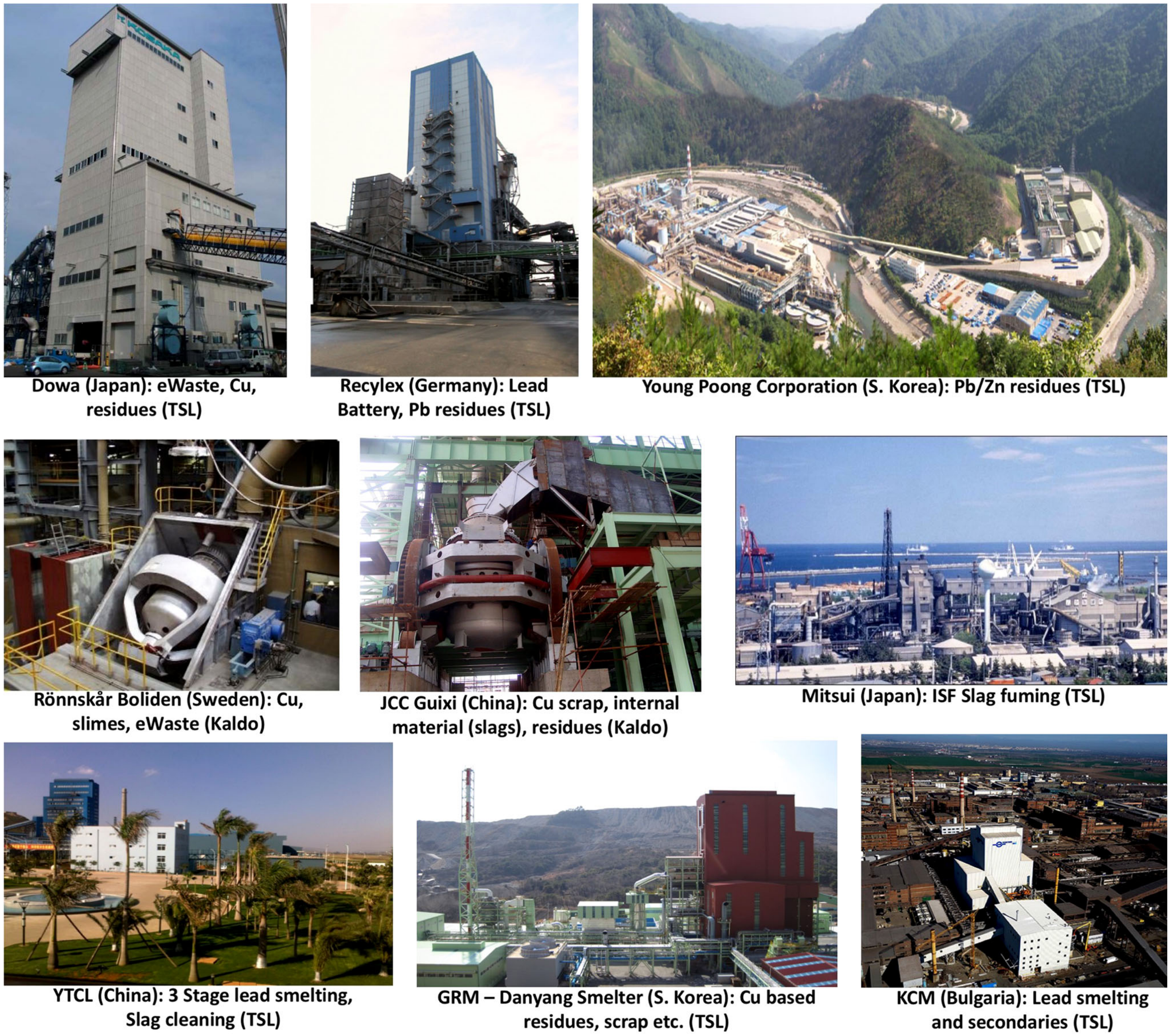

Fig. 16—Various examples of metallurgical reactors[89,90] that help close the loop within visionary CECs, the key innovators within the global CE system.

industry. This implies that corporations that have as their mission vision and courage to engage in the complete cycle, as depicted in Figs. 1 and 2, will advance sustainability and will be the future leaders due to among others their sophisticated and agile multibase metal and minor metallurgical processing flow sheets. Resource corporations may in the short term be more profitable through a linear product portfolio, *i.e.*, mine-to-mill, dig-and-ship, or oil well-to-refinery, which may be and probably is inherently unsustainable in the long run. Having said that, the CE paradigm opens up great opportunity; it opens up the paradigm ''Circular Economy Corporation (CEC).'' Acknowledging the fact that metals and their associated WoM are probably presently the only anthropogenic system that can hesitantly be labeled sustainable opens attractive perspectives for resource and metal producing corporations. A rethink and shift in resource and recycling metal and alloy producing corporation vision will contribute significantly to ensuring a sustainable future for the planet.

According to SGS,[91] geometallurgy is, ''The integration of geological, mining, metallurgical, environmental and economic information to maximize the net present value of an orebody while minimizing technical and operational risk.'' The CE corporation will embrace geometallurgy of primary orebodies as well as that from recyclates, residues, *etc.*, as shown in Figure 1. Some sustainably smart corporations have built their processing infrastructure on significantly more than one base metal and technology metal processing infrastructure (*e.g.*, Metal Wheel[46]) to capture as many as possible minor, technology, and other valuable metals in highly sophisticated and sustainability conscious refining infrastructures, *e.g.*, DOWA (Japan),[92] Nyrstar (Switzerland),[93] Umicore (Belgium),[94] New Boliden (Sweden),[95] Korea Zinc (South Korea),[96] and Aurubis (Germany).[97] These innovative companies have created processing technologies over many sites globally to close the loop in their respective corporations in a smart and agile manner. In summary, the following may be asserted or demonstrated.

1. Resource, metal producing, and recycling corporations are excellently positioned within the CE paradigm to contribute significantly to a resource efficient CE.
2. Innovative CECs will drive their respective corporations to be economically optimal while at the same time also maximizing RE.
3. CECs embracing the larger picture (Figures 1 and 2) will be sustainability leaders. These corporations will have wide portfolios of metal production and link closely with OEMs.
4. System modeling and optimization should be used by corporations to ensure global optima are obtained for RE while at the same time setting the bar for a CE and highlighting metallurgical infrastructure criticality.
5. Policy makers should be made aware of the critical importance of metallurgical infrastructure to ensure there exists agility and system flexibility to deal with the vastly complex metal and material mixtures in products and, hence, to close the loop of the CE system.
6. Thorough technological, economic, and fundamental knowledge of the CE system permits the quantification of the limits of recycling and a CE, creating a fundamental basis for the formulation of environmental.
7. CE simulation models are linked to environmental LCA tools, providing the fundamental technological and statistical basis for the calculations of RI and RE.
8. A fundamental and technological basis for DfR guidelines is hence provided supporting eco-design by providing fundamental knowledge on CE systems and DfR.
9. Future DfR will link CAD and additive manufacturing *via* m-IoT process simulation to predict recyclate qualities that feed process metallurgy.
10. To realize an m-IoT requires the assimilation of not only real-time process data but also thermodynamic data to calibrate the required system models that quantify all the losses, including entropy.[84]
11. The given theoretical engineering foundation provides a basis for the formulation of RE and provides the basis for CEE.
12. A CEE approach will provide the true techno-economic limits of a CE and highlight the importance of an agile and complete metallurgical infrastructure.

D. *Delivering the CE*

Best practice and good governance in resource and metallurgical corporations make them excellently suited to create CECs. This is the easiest way to show the potential of a CE. This will demonstrate the key role the metallurgical industry plays in establishing the m-IoT within the CE. This provides the metallurgical industry with the opportunity to play a leading role in digitalizing the CE system and linking all reactors and systems within the m-IoT paradigm, as shown by Figure 9. This rigor enables understanding and will help innovate the CE system but also keep feet on the ground and provide understanding of the limits of a CE system within the context of complex society defined by rather complex nonlinear and thermodynamically based interactions, as shown by the m-IoT reflected in Figure 8.

Furthermore, the significant opportunity that CE brings with it is that it shows how important metals are, forming its fabric through its complex interlinkage of metals and materials in the WoM. Metal associations[16,17,98–104] have a significant task to bring metals into the full focus of society, showing their respective importance (often operating in silos); it could be recommended that these associations get together even closer to ensure that the full metallurgical processing infrastructure is in optimal harmony to maximize RE (thus de-silo and service all metals at the same time). This will help to ensure that the so important metallurgical infrastructure remains intact, revealing, in fact, not only the criticality of materials, but also the criticality of metallurgical infrastructure. Therefore, together with the associations representing the producers of products,[105–108] the metal associations are excellently positioned to play a key role within the CE. Together with the associations, the innovation being driven through the EU's Knowledge Innovation Community (KIC), and more specifically through the EIT Raw Materials KIC,[109] is crucial to create the CE. This provides a platform for informing policy,[110] and a basis is created from which the CE can develop its fullest potential.

E. *Some Final Thoughts and Questions*

In the introduction, the statement of this award lecture was: "Process metallurgy is a key enabler for a CE and will help much to deliver its noble goals through digitalizing the complete WoM.". Having shown the various opportunities, limits, infrastructure, technology, tools, and methods of process metallurgy and recycling within the CE, the following lists some final questions with which I would like to conclude.

1. Will process metallurgy indeed be a key enabler for a CE due to metal's high intrinsic recyclability properties?
2. Can process metallurgy iRE by digitalizing the WoM?
3. Will the sophisticated tools of CEE help to deliver the CE's goals?

4. Can process metallurgy help shape CE policy as it truly reveals its limitations?
5. Is the m-IoT a key that will give process metallurgy the center of the CE stage?
6. Therefore, will the criticality of metallurgical infrastructure, *i.e.*, m-IoT, be observed and innovatively developed within new CE business models?
7. Will metallurgical infrastructure be built and innovated by wise policy and not disrupted by unwise short-term business decisions that lack engineering and technology insight and depth?
8. Carrier metal metallurgy (Metal Wheel[46]) has been optimized for minerals over many years. Consumer-designed minerals and the CE require this same basic metallurgical infrastructure (which policy must protect), but it requires more than these to be significantly more strongly interlinked in the WoM. Therefore, key questions, for example, are as follows:

   a. "Will the future integrated steel plant be a smart linkage of blast, bath, and EAF furnaces and much more strongly integrated to nonferrous metallurgy, as shown by Figure 8?"
   b. "Will metallurgy unleash its full strength and power by de-siloing it and integrating it into a full WoM and enabling the full potential of a CE?"
   c. "Will the disruptive business models of CE be developed to accommodate this smart agile new business and technology environment that also embraces key metallurgical systems and infrastructure?"

9. What is the role of consumer behavior in consumption and collection in the CE?
10. Will our metallurgical and recycling simulation models and our impact be of use to inform climate change in a simple but game-changing manner?
11. Material scientists and developers should in future evaluate the resource efficiency of their new materials to check where these report to when recycled from complex EoL products. Thus the important questions to be addressed are: Will developing new materials in future also consider Fig. 1 in a PCR context to check CE relevance? Will material scientists come closer again to process metallurgists and engineers in a CE paradigm with its RE system (re)design thinking?

Ultimately, the answers to all these and other incisive questions may simply be, "Consume less!" Our presently rather complex consumerism simply creates too much entropy in the form of finely dissipated materials and metals in addition to the large amount of energy we consume. Thus, maximizing RE, as shown in Figure 6 (bottom), and visualizing this to empower the consumer is crucial by suitable RI visualization.[110] Furthermore, material recycling index visualization shows the recovery of each individual element in a product. We have called it the "material recycling label," visualized in the form of an "element flower."[111] This will help much to inform the environmental and CE communities that more complex models are required than the simple MFA models that are presently used to inform CE policy. It is interesting to note that a recent policy publication of Germany's distinguished "Friedrich Ebert Stiftung"[112] mentions the thermodynamic limitations of a CE, citing our United Nations Environmental Program (UNEP) report on metal recycling. This UNEP report discusses in detail these limitations in addition to metallurgical processing technology and its sophisticated systems.[5,7,9] The digitalized process metallurgy's SIMP and m-IoT may provide the CEE tools[11,40,41,111] to guide a path toward a sustainable society. These tools will help advise policy of the opportunities and limits of a CE society on a theoretical and techno-economic basis. Above all it will also show the importance of a metallurgy and its high-tech processing infrastructure at the heart of a CE.

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NOMENCLATURE

AI	Artificial intelligence
CAPEX	Capital expenditure
CAD	Computer-aided design
CAE	Computer-aided engineering
CE	Circular economy
CEC	Circular economy corporation
CEE	Circular economy engineering
CFD	Computational fluid dynamics
DEM	Discrete element methods
DfR	Design for recycling
DfRE	Design for resource efficiency
DfS	Design for sustainability
EoL	End-of-life (of products)
EE	Energy efficiency (as used to label products)
EU	European Union

iRE	Inform resource efficiency
IE	Industrial ecology
IoT	Internet of things
KIC	Knowledge Innovation Community of the EU's EIT
m-IoT	Metallurgical internet of things
LC	Liberation class
LCA	Life-cycle assessment
LME	London Metal Exchange
MFA	Material flow analysis
MLA	Mineral liberation analysis
OEM	Original equipment manufacturer (for products)
OPEX	Operational expenditure
PCR	Product centric recycling
RE	Resource efficiency: reducing the total environmental impact of the production and consumption of goods and services, from raw material extraction to final use and disposal (UNEP, http://www.unep.org)
RI	Recycling index
SIMP	System integrated material production
TSL	Top submerged lance smelting technology (Ausmelt-Outotec and ISASMELT™)
UNEP	United Nations Environmental Program (http://www.unep.org)
WoM	Web of Metals (and Web of Things)

REFERENCES

1. European Union: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee of the Regions. *Closing the loop—An EU Action Plan for the Circular Economy*. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52014DC0398&from=EN, 2015. Accessed 16 May 2016.
2. European Union: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee of the Regions: *On the Review of the List of Critical Raw Materials for the EU and the Implementation of the Raw Materials Initiative*. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52014DC0297&from=EN, 2014. Accessed 16 May 2016.
3. European Copper Institute: *DG GROWTH Conference on Exchanges of Good Practices on Metal By-Products Recovery*. http://copperalliance.eu and https://www.youtube.com/watch?v=0WE72HB7asY, 2015. Accessed 13 May 2016.
4. M.A. Reuter and A. van Schaik: *MRS Bull*., 2012, vol. 37 (4), pp. 339–47.
5. M.A. Reuter, C. Hudson, A. Van Schaik, K. Heiskanen, C. Meskers, and C. Hagelüken: United Nations Environmental Protection Report. http://www.unep.org/resourcepanel/Portals/50244/publications/UNEP_report2b_RecyclingOpportunities_130919.pdf, 2013. Accessed 13 May 2016 (over 400,000 downloads May 2013–Oct. 2015).
6. M.A. Reuter, K. Heiskanen, U. Boin, A. van Schaik, E. Verhoef, and Y. Yang: *The Metrics of Material and Metal Ecology, Harmonizing the Resource, Technology and Environmental Cycles*, 1st ed., Elsevier BV, Amsterdam, 2005.
7. M.A. Reuter and A. van Schaik: in *Encyclopedia of Ecology*, 1st ed., S.E. Jorgensen and B.D. Faith, eds., Elsevier B.V., Oxford, 2008, pp. 2247–60.
8. E. Worrel and M.A. Reuter: *Handbook of Recycling*, 1st ed., Elsevier B.V, Amsterdam, 2014.
9. A. Van Schaik and M.A. Reuter: in *Handbook of Recycling*, E. Worrel and M.A. Reuter, eds., Elsevier, Amsterdam, 2014, pp. 307–78.
10. M.A. Reuter: *Miner. Eng*., 1998, vol. 11 (10), pp. 891–917.
11. M.A. Reuter, A. van Schaik, and J. Gediga: *Int. J. Life Cycle Assess*., 2015, vol. 20 (5), pp. 671–93.
12. A. van Schaik and M.A. Reuter: *Miner. Eng*., 2007, vol. 20, pp. 875–90.
13. M.A. Reuter and J.S.J. van Deventer: *Int. J. Miner. Process*., 1990, vol. 28, pp. 15–43.
14. United Nations Environmental Programme (UNEP): http://www.unep.org, 2016. Accessed 13 May 2016.
15. A. van Schaik and M.A. Reuter: *Miner. Eng*., 2010, vol. 23, pp. 192–210.
16. World Steel Organization: http://www.worldsteel.org, 2016. Accessed 13 May 2016.
17. Eurometaux: http://www.eurometaux.org, 2016. Accessed 13 May 2016.
18. K. Miettinen: *Nonlinear Multiobjective Optimization*, 1st ed., vol. 12, Kluwer's International Series in Operations Research & Management Science, Kluwer Academic Publishers, Boston, 1999.
19. Y. Jin: *Swarm Evol. Comput*., 2011, vol. 1, pp. 61–70.
20. Python Software Foundation: *Surrogate Optimization Toolbox*, https://pypi.python.org/pypi/pySOT/0.1.0, 2016. Accessed 13 May 2016 (Python also has a wealth of other toolboxes, https://www.python.org).
21. Mathematic: https://reference.wolfram.com/language/guide/Optimization.html, 2016. Accessed 13 May 2016 (Mathematica also has a wealth of other toolboxes, see https://www.wolfram.com/mathematica/).
22. AMPL: *A Mathematical Programming Language, Building Optimization into Large-Scale Applications, Intuitive Algebraic Modeling System*, http://ampl.com, 2016. Accessed 13 May 2016.
23. Aspen Plus, AspenTech: *Chemical Process Optimization Software*, http://www.aspentech.com, 2016. Accessed 13 May 2016.
24. Cycad Process: *Metallurgical Process Simulation*, http://www.cycadprocess.com, 2016. Accessed 13 May 2016.
25. gPROMS: *Process Systems Enterprise, Process Modelling Platform*, http://www.psenterprise.com, 2016. Accessed 13 May 2016.
26. HSC 9.1 and HSC Sim, Outotec: *Pure Substance Database, Various Standard Application Modules, Process Simulation Linking Minerals and Metallurgical Processing, Environmental Assessment*, http://www.outotec.com/hsc linked to the Proscon control system http://www.outotec.com/en/Products–services/Analyzers-and-automation/Process-control/Outotec-Proscon/ and control platform http://www.outotec.com/en/Products–services/Analyzers-and-automation/, 2016. Accessed 13 May 2016.
27. JKSimMet, JKtech: *Minerals Processing Simulation*, http://jktech.com.au, 2016. Accessed 13 May 2016.
28. Mathworks, Matlab and Simulink: *Engineering Computing Software in Numerous Toolboxes*, http://www.mathworks.com/products/, 2016. Accessed 13 May 2016 (there is a variety of open source software that could also be used, e.g., https://www.gnu.org/software/octave/, http://www.sagemath.org).
29. METSIM: *Metallurgical Steady-State and Dynamic Flowsheeting and Simulation*, http://www.metsim.com, 2016. Accessed 13 May 2016.
30. R.P. King: *Modelling and Simulation of Mineral Processing Systems,* 1st ed., Butterworth-Heinemann, Oxford http://www.mineraltech.com/MODSIM/, 2001. Accessed 13 May 2016.
31. SimSci PRO/II, Schneider Electric: *Process Simulation Software*, http://software.schneider-electric.com/simsci/, 2016. Accessed 13 May 2016.
32. USIM PAC: *Minerals and Hydrometallurgical Process Simulation*, http://www.caspeo.net/USIMPAC, 2016. Accessed 13 May 2016.
33. PI System, OSIsoft: http://www.osisoft.com/Default.aspx, 2016. Accessed 13 May 2016.
34. CALPHAD: *Phase Diagrams*, http://www.opencalphad.com, 2016. Accessed 13 May 2016.
35. FactSage, GTT-Technologies and Thermfact: *Various Databases for Metallic and Non-Metallic Systems Including Non-Ideal Solutions, Complex Equilibria and Phase Diagrams*, http://www.factsage.com (including ChemApp, ChemSheet, and SimuSage), http://www.gtt-technologies.de, 2016. Accessed 13 May 2016.
36. MTDATA: *Phase Diagrams*, National Physics Laboratory, www.npl.co.uk/science-technology/mathematics-modelling-and-simulation/mtdata/, 2016. Accessed 13 May 2016.

37. Pandat: *Computherm*, http://www.computherm.com, 2016. Accessed 13 May 2016.
38. Thermocalc: *Thermocalc AB*, http://www.thermocalc.com, 2016. Accessed 13 May 2016.
39. M.A. Reuter, A. van Schaik, O. Ignatenko, and G.J. de Haan: *Miner. Eng.*, 2006, vol. 19 (5), pp. 433–49.
40. I. Rönnlund, M.A. Reuter, S. Horn, J. Aho, M. Päällysaho, L. Ylimäki, and T. Pursula: *Int. J. Life Cycle Assess.*, 2016, Part 1—online 6 May 2016.
41. I. Rönnlund, M.A. Reuter, S. Horn, J. Aho, M. Päällysaho, L. Ylimäki, and T. Pursula: *Int. J. Life Cycle Assess.*, 2016, Part 2—online 8 May 2016.
42. M.A. Reuter and I. Kojo: *World Metall. Erzmet.*, 2014, vol. 67 (1), pp. 46–53.
43. M.A. Reuter, R. Matusewicz, and A. van Schaik: *World Metall. Erzmet.*, 2015, vol. 68 (3), pp. 132–46.
44. M.A. Reuter and Y. Yang: in *Smithells Metals Reference Book*, 8th ed., Butterworth-Heinemann, Elsevier B.V., Amsterdam, 2004, pp. 40-16–40-29.
45. European Union: Commission Delegated Regulation No. 874/2012 of 12 July 2012, supplementing Directive 2010/30/EU of the European Parliament and of the Council with regard to energy labelling of electrical lamps and luminaires, 2012.
46. E. Verhoef, G. Dijkema, and M.A. Reuter: *J. Ind. Ecol.*, 2004, vol. 8 (1–2), pp. 23–43.
47. S. Sudhölter, M.A. Reuter, and J. Krüger: *Metall. Mater. Trans. B*, 1996, vol. 27B, pp. 1031–44.
48. A. van Schaik and M.A. Reuter: *Resour. Conserv. Recycl.*, 2004, vol. 40 (4), pp. 301–28.
49. B. Castro, H. Remmerswal, H. Brezet, A. van Schaik, and M.A. Reuter: *Int. J. Miner. Process.*, 2005, vol. 75 (3–4), pp. 255–81.
50. S. Creedy, A. Glinin, R. Matusewicz, S. Hughes, and M.A. Reuter: *World Metall. Erzmet.*, 2013, vol. 66 (4), pp. 230–35.
51. General Electric: *Proficy CSense—Real-Time Big-Data Analysis or Process and System Data*, http://www.geautomation.com/products/proficy-csense, 2016. Accessed 13 May 2016.
52. D. Moolman, M.A. Reuter, and A. van Schaik: *World Metall. Erzmet.*, 2005, vol. 58 (3), pp. 113–24.
53. SAS, SAS Institute Inc.: *Statistical Analysis Software*, http://www.sas.com/en_us/home.html, 2016. Accessed 13 May 2016.
54. WEDGE, Savcor: *Fast Online Process Diagnostics*, http://www.savcor.com/solutions/process-diagnostics/, 2016. Accessed 13 May 2016.
55. G2, Gensym: *Real-Time Process Optimization and Reasoning Software*, http://www.gensym.com, 2016. Accessed 13 May 2016.
56. M.A. Reuter, T.J. van der Walt, and J.S.J. van Deventer: *Metall. Mater. Trans. B*, 1992, vol. 23B, pp. 641–50.
57. M.A. Reuter: *Erzmetallurgy*, 1993, vol. 46 (6), pp. 369–76.
58. C. Aldrich, J.S.J. Van Deventer, and M.A. Reuter: *Miner. Eng.*, 1994, vol. 7, pp. 793–809.
59. M.A. Reuter, C. Pretorius, C. West, P. Dixon, and M. Oosthuizen: *J. Met.*, 1996, vol. 48 (12), pp. 51–53.
60. G.R.F. Alvear Flores, S. Nikolic, and P.J. Mackey: *J. Met.*, 2014, vol. 66 (5), pp. 823–32.
61. G.A. Georgalli, J.J. Eksteen, and M.A. Reuter: *Miner. Eng.*, 2002, vol. 15 (11), pp. 909–17.
62. J. Eksteen and M.A. Reuter: *Miner. Eng.*, 2006, vol. 19 (11), pp. 1174–84.
63. B. Zhou, Y. Yang, M.A. Reuter, and U.M.J. Boin: *Miner. Eng.*, 2006, vol. 19 (3), pp. 299–308.
64. M.A. Reuter and J.S.J. van Deventer: *Chem. Eng. Sci.*, 1993, vol. 48 (7), pp. 1281–97.
65. ANSYS: *Computational Fluid Dynamics*, http://www.ansys.com, 2016. Accessed 13 May 2016.
66. OpenFOAM: *ESI-OpenCFD, Open Source CFDC*, http://www.openfoam.com, 2016. Accessed 13 May 2016.
67. modeFRONTIER: *Integration Platform for Multi-objective and Multi-disciplinary Optimization, Provides a Seamless Coupling with Third Party Engineering Tools, Enables the Automation of the Design Simulation Process, and Facilitates Analytic Decision Making*, http://www.esteco.com, 2016. Accessed 13 May 2016.
68. DCS Computing: *Committed to Excellence in Computational Modelling and Engineering Solutions for Flow Processes*, http://www.dcs-computing.com/home, 2016. Accessed 13 May 2016.
69. H.P. Zhu, Z.Y. Zhou, R.Y. Yang, and A.B. Yu: *Chem. Eng. Sci.*, 2002, vol. 62 (13), pp. 3378–96.
70. N. Huda, J. Naser, G. Brooks, M.A. Reuter, and R.W. Matusewicz: *Metall. Mater. Trans. B*, 2012, vol. 43 (1), pp. 39–55.
71. N. Huda, J. Naser, G. Brooks, M.A. Reuter, and R.W. Matusewicz: *Metall. Mater. Trans. B*, 2012, vol. 43, pp. 1054–68.
72. E. Scheepers, Y. Yang, A.T. Adema, R. Boom, and M.A. Reuter: *Metall. Mater. Trans. B*, 2010, vol. 41B, pp. 990–1005.
73. W.M. Husslage, M.A. Reuter, R.H. Heerema, T. Bakker, and A.G.S. Steeghs: *Metall. Mater. Trans. B*, 2005, vol. 36 (6), pp. 765–76.
74. Tomra (and Titech) Sorting Equipment, 2016, https://www.tomra.com. Accessed 13 May 2016.
75. *D X-Ray Tomography*, http://www.zeiss.com/microscopy/en_us/products/x-ray-microscopy.html and http://www.xre.be, 2016. Accessed 13 May 2016.
76. Mineral Liberation Analysis (MLA): https://www.fei.com/products/sem/qemscan/, 2016. Accessed 13 May 2016.
77. R.G. Fandrich, Y. Gu, D. Burrows, and K. Moeller: *Int. J. Miner. Process.*, 2007, vol. 84 (1–4), pp. 310–20.
78. GaBi: *Thinkstep, Environmental Assessment*, http://www.gabi-software.com/international/index/, 2016. Accessed 13 May 2016.
79. OpenLCA: *Open LCA Organization, Environmental Assessment*, http://www.openlca.org, 2016. Accessed 13 May 2016.
80. Simapro 8: *Pre Consultants, Environmental Assessment*, https://www.pre-sustainability.com/simapro, 2016. Accessed 13 May 2016.
81. S.H. Amini, J.A.M. Remmerswaal, M.B. Castro, and M.A. Reuter: *J. Cleaner Prod.*, 2007, vol. 15 (10), pp. 907–13.
82. X. Chi, M. Streicher-Porte, M.Y.L. Wang, and M.A. Reuter: *Waste Manag.*, 2011, vol. 31 (4), pp. 731–42.
83. Ellen MacArthur Foundation: https://www.ellenmacarthurfoundation.org/circular-economy/overview/concept, 2016. Accessed 13 May 2016.
84. M.A.H. Shuva, M.A. Rhamdhani, G.A. Brooks, S. Masood, and M.A. Reuter: *J. Cleaner Prod.*, 2016. Accessed 6 May 2016.
85. World Business Council for Sustainable Development—WBCSD: http://www.wbcsd.org/home.aspx, 2016. Accessed 13 May 2016.
86. Water Footprint Network: http://waterfootprint.org/en/, 2016. Accessed 13 May 2016.
87. Global Footprint Network: http://www.footprintnetwork.org/en/index.php/GFN/, 2016. Accessed 13 May 2016.
88. International Resource Panel (IRP): http://www.unep.org/resourcepanel/ as a part of the United Nations Environmental Programme, 2016.[14] Accessed 13 May 2016.
89. M.A. Reuter, J.J. Eksteen, and A. van Schaik: *Yazawa Int. Symp. on Metallurgical and Materials Processing: Principles and Technologies, Mar. 3–6, 2003*, vol. 1, San Diego, CA, 2003, pp. 1005–18.
90. Outotec TSL and Kaldo references: *Smelting of Concentrates, Residue, Wastes, Scrap, eWaste*, http://www.outotec.com/en/About-us/Our-technologies/Smelting/Ausmelt-smelting-and-converting/ and http://www.outotec.com/en/About-us/Our-technologies/Recycling-and-residues/, 2016. Accessed 13 May 2016.
91. SGS: http://www.sgs.com/en/mining/exploration-services/geometallurgy, 2016. Accessed 13 May 2016.
92. Dowa Holdings Co., Ltd.: http://www.dowa.co.jp/index_e.html, 2016. Accessed 13 May 2016.
93. Nyrstar: http://www.nyrstar.com/Pages/default.aspx, 2016. Accessed 13 May 2016.
94. Umicore: http://www.umicore.com, 2016. Accessed 13 May 2016.
95. Boliden: http://www.boliden.com, 2016. Accessed 13 May 2016.
96. Korea Zinc Co., Ltd.: http://www.koreazinc.co.kr/english/main/page/main.aspx, 2016. Accessed 13 May 2016.
97. Aurubis AG: *Germany*, www.aurubis.com, 2016. Accessed 22 July 2016.
98. World Aluminium: www.world-aluminium.org (also see http://www.aluminum.org, www.european-aluminium.eu), 2016. Accessed 13 May 2016.
99. International Zinc Association (IZA): www.zinc.org, 2016. Accessed 13 May 2016.
100. International Nickel Association (INA): www.nickelinstitute.org, 2016. Accessed 13 May 2016.

101. International Chrome Development Association (ICDA): http://www.icdacr.com/index.php?lang=en, 2016. Accessed 13 May 2016.
102. International Lead Association (ILA): www.ila-lead.org, 2016. Accessed 13 May 2016.
103. Copper Alliance: www.copperalliance.org (also see www.copper.org, http://www.icsg.org, www.copperalliance.eu), 2016. Accessed 13 May 2016.
104. International Lead Zinc Study Group (ILZSG): http://www.ilzsg.org/static/home.aspx, 2016. Accessed 13 May 2016.
105. WEEE Forum: http://www.weee-forum.org, 2016. Accessed 13 May 2016.
106. Bureau of International Recycling (BIR): http://www.bir.org, 2016. Accessed 13 May 2016.
107. Digital Europe: http://www.digitaleurope.org, 2016. Accessed 13 May 2016.
108. Electrical Equipment Representative Association (EERA): http://www.eera.org, 2016. Accessed 13 May 2016.
109. EIT Raw Materials Knowledge Innovation Community (KIC): http://eitrawmaterials.eu, 2016. Accessed 13 May 2016.
110. M.A. Reuter and A. van Schaik: *Annal. Mines*, 2016, vol. 82, pp. 62–6.
111. A. van Schaik and M.A. Reuter: *World Metall. Erzmet.*, 2016, vol. 69, pp. 201–16.
112. H. Wilts: Deutschland auf dem Weg in die Kreislaufwirtschaft, FRIEDRICH-EBERT-STIFTUNG—Wirtschafts- und Sozialpolitik, 2016, wiso-news@fes.de.