Towards sustainable metal cycles:

the case of copper

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Cover illustration: Stall roasting of copper matte

From *De Re Metallica* by Georgius Agricola, 1556

Per
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and
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DECLARATION

I declare that all work in this thesis is my own original work, unless stated otherwise.

This thesis is submitted for the degree:
Doctor of Philosophy, at the University of Sydney.
Material in this thesis has not been submitted for any other degree.

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ABSTRACT

Developing an approach that delivers improved environmental performance for metal cycles is the aim of this thesis. Integral to the sustainable use of metals is the need to reduce environmental impacts associated with the mining, refining and recycling activities that supply metal to the economy. Currently, the links between the location and duration of these activities, their resultant impacts and the responsible parties are poorly characterised. Consequently, the changes to technology infrastructure and material flow patterns that are required to achieve sustainable metal cycles remain unclear to both industry and government actors. To address this problem, a holistic two-part methodology is developed.

Firstly, a reference schema is developed to address the complexity of structuring analyses of the material chain at different geographical and time scales. The schema identifies actors and system variables at each scale of analysis and guides the level of information detail and performance indicators to be used in material chain characterisation. Material chain characterisation involves modelling material and energy flows for current activities as a series of connected nodes and linking these flows to resultant environmental impacts. The approach identifies the material chain activity responsible for each environmental impact and makes trade-offs between impacts explicit. Sensitivity analysis of the models identifies the key variables that enhance performance. The influence of actors over these variables is assessed to target areas for improvement.

This first part of the methodology is illustrated using case studies that assess the current performance of copper material chain configurations at different geographical scales within the reference schema.

The analysis of global material and energy flows indicates that the majority of environmental burden in the copper material chain is attributable to primary refining of metal from ore. Modelling of the dominant primary refining technologies using region-specific information for ore grade, technology mix and energy mix reveals that the total environmental impact differs by factors of 2–10 between world regions. The study of refined copper imports to Europe from various regions outside of Europe reveals that lower global warming impacts are achieved at the expense of increased local impacts from the producing regions. Overall, only limited improvements are possible without investing in new technology infrastructure.

Evaluation of an innovative copper refining technology finds that collaboration with clean energy suppliers reduces global warming impacts more than changing process design parameters. To better assess the local impacts that are directly controllable by the technology operator, a new indicator incorporating the stability of solid waste is developed.

In the second part of the methodology, the link established between actors, their control over key system variables and resultant impacts is used to design preferred future configurations for the material chain. Dynamic models are developed to evaluate transition paths towards preferred futures for individual and collaborative action by industry in the context of externally changing variables (for example, increasing demand for copper and declining available ore grades).

Both new copper technology infrastructure and new material flow patterns are assessed in transitions toward preferred futures for a case study of the United States. The improvements resulting from the introduction of new primary refining technology by individual actors are negated by increasing impacts from declining copper ore grades over time. Achieving a combined reduction in local and global environmental impacts requires collaboration between industry actors to immediately increase the recycling of secondary scrap.

Significantly, this methodology links actor decisions with their impacts across scales to prompt accountability for current performance and guide useful collaborations between actors. The methodology then delivers a comprehensive assessment of the scale and timing of required interventions to achieve more sustainable metal cycles.

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