Agent Based Modeling of large-scale socio-technical metal networks

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Abstract

Metals production and consumption networks are complex Large Scale Socio-Technical Systems, consisting of many technical installations, companies operating them, at a global scale, with large environmental impacts. Understanding their dynamics and behavior requires models that are capable of capturing technical, social, economic and other dimensions. Modeling in the metals domain has traditionally focused on technical and metallurgical aspects. Agent Based Modeling (ABM), a relatively new technique in the metals domain, is a tool from the Complex Adaptive Systems field that allows investigation of the change of metals production and consumption networks structure, as they evolve towards a more sustainable state. This paper presents two examples of ABMs of metals networks that illustrate how the modeling technique can be used and the types of insights it offers.

Introduction

Large scale socio-technical system

Large-Scale Socio-Technical Systems (λ-systems) are a class of systems that span technical installations embedded in social networks, by which a large-scale, complex socio-technical systems emerge [1]. Examples of λ-systems include organizations and institutions that develop around and sustain a particular industrial system, be it a single plant, an industrial complex, a set of interconnected supply chains or an entire infrastructure. They consist of a large number of diverse technical artifacts, such as machines, factories, pipelines and wires. They also consist of social components, such as policies, organizations and institutions that develop around the technical components. Regional industrial clusters, interconnected power grids, multimodal transport networks and telecommunication networks are examples of such systems. λ-systems thus consist of interwoven physical and social networks. There are multiple connections between these systems. These connections have multiple characteristics and are of many different types; system content, structure and boundaries shift and evolve. At the global level there is no central coordinator, but order and structure are emergent from widely distributed bottom-up interactions of subsystems, some of which do have local central control, and some of which are fully dispersed.

John H. Holland [2] defines Complex Adaptive Systems (CAS) as:

...a dynamic network of many agents (which may represent cells, species, individuals, firms, nations) acting in parallel, constantly acting and reacting to what the other agents are doing. The control of a CAS tends to be highly
dispersed and decentralized. If there is to be any coherent behavior in the system, it has to arise from competition and cooperation among the agents themselves. The overall behavior of the system is the result of a huge number of decisions made every moment by many individual agents.

It is clear that λ-systems can be viewed as Complex Adaptive Systems.

**Metals network are complex λ-systems**

Metals networks can be categorized as complex λ-systems. They include vastly complex interacting social and technical components that span the globe. They necessitate the movement of enormous masses of overburden and large amounts of materials in the form of metals, products or scrap for example, and consume significant amounts of water and energy. Because of the size of investments necessary, companies involved are often very large multinationals, operating across many economic and political environments. The complexity of these networks is further increased by the fact that products are interlinked in production, consumption and end of life. Due to the fact that most metals are co-produced with other metals, a change in production volume of one will likely affect the availability of another. Many metals also have functional substitutes, meaning that increased consumption of one may often be linked with decreased consumption of another.

Understanding the behavior of Complex Adaptive Systems is difficult, and actively shaping it is even more so. Given the physical, economic, social and ecological scale of the impacts these systems have, we must be able to understand and possibly shape them if we are ever to achieve a sustainable world. As it is impossible to perform global scale real world experiments, we can not directly test our proposed interventions. We therefore must turn to simulation in order to understand the impacts of potential changes to the metals λ-systems.

**Understanding and shaping λ-systems through simulation**

**Modeling metals networks**

Simulations and models are one of the quantitative tools available for exploration of system behavior and possible futures. Simulation modeling is not an unfamiliar approach in metals and minerals research, although it is most often applied at the micro level. Computational fluid dynamics (CFD) is applied in the optimization of engineering processes such as surface engineering and metal casting [3], as well as smelting processes and waste heat recovery [4]. Simulation modeling is also applied at the material level. An example here is the use of a kinetic Monte Carlo Potts model for simulating microstructural evolution [5].

Macro-level simulation modeling approaches are less common in metals and minerals research. Many macro-level models in this area are static analyses of material flows within a certain industry or geographical area. Notable here are several studies by participants in Yale’s STAF project, who have analyzed the global stocks and flows of various metals [6]. Dynamic macro-level models related to the metals and minerals industry most often apply a system dynamics methodology, which is especially useful for understanding the impact of feedback loops on system-level behavior in complex systems. Examples are [7, 8, 9]. Also notable here is [10], which presents a simulation model of comminution and liberation of end-of-life products during recycling as a function of product design variables. It is often argued that sustainability requires a change in the structure of our production and consumption systems [11, 12]. As system dynamics modeling assumes fixed structure between
system elements, it does not allow for the bottom-up emergence of this structure, and is thus unsuitable to model the process of structural change. We need a different modeling approach.

Agent Based Modeling

Agent-based modelling (ABM) is a technique stemming from Complex Adaptive Systems research, and is based on the generative science paradigm [13] that describes complex behaviors as generative processes. The central principle is that phenomena can be described in terms of interconnected networks of (relatively) simple units. In this approach deterministic and finite rules and placed in interacting entities generate complex behavior. Epstein [13] describes this generative process as “Situate an initial population of autonomous heterogeneous agents in a relevant spatial environment; allow them to interact according to simple local rules, and thereby generate - or 'grow' - the macroscopic regularity from the bottom up.” Furthermore, Shalizi [14] states that

“An agent is a persistent thing which has some state we find worth representing, and which interacts with other agents, mutually modifying each others’ states. The components of an agent-based model are a collection of agents and their states, the rules governing the interactions of the agents, and the environment within which they live.”

Agents are computer programs that exist in some environment that are capable of flexible, autonomous action in order to meet their design objectives [15].

Agent based models have extensively been used in business literature [16, 17], are regularly used in economics [18], land use planning [19], ecology [20] and most recently, Buchanan [21] has discussed the relevance of ABM for modeling financial systems and their potential for preventing a new financial crisis.

ABMs in metals and minerals research are relatively few and far between. At the moment of writing, the JOM journal does not have a single paper using ABM as a modeling technique. Maciol et al [22] present of the few examples to be found in the field, investigating the usefulness of agent-based modeling to assess the impact of marketing strategy on the sales volumes of steel products manufacturers.

Two metals cases

We will now proceed to describe two cases in which ABM has been applied to model metals networks. The cases described below share a common basic understanding of agents and the form of their interactions. The smallest element in a λ-system such as a metals network is a firm and its production facilities. The employees and management of the firm form a social network that uses economic and business reasoning to decide on suppliers, product pricing, (dis)investments, etc. It has to deal with changing markets and policy environments, and faces stiff competition to survive. The physical assets operated by the firm have to meet performance targets, have a designed capacity and a certain environmental impact. These aspects involve many different formalisms in their description. On top of that, the firm’s technology changes over time, as does the social network that makes decisions.

From agents state and behavior to emergent network structure As illustrated in Figure 1, in both of these cases, an agent’s state is conceptualized to consist of technical and economic parameters. Technical aspects of the agent are based on the input-output perspective of the field of Process Systems Engineering. From this perspective, agents are nodes that transform
mass and energy from one state into another, and the edges between them are flows of mass and energy. Economic aspects of the agent are drawn from the field of Corporate Finance [23, 24], which describes entities in terms of assets, debt, operational costs, investment costs, etc. These variables can be seen as the moving parts of the economic machine of the agent.

![Generic Agent layout](image)

Figure 1: Generic Agent layout

While an agent’s state is described by technical and economic parameters, its behavior is determined by the interaction of this state with the agent’s technical and economic decision rules. Technical decision rules are based on the law of conservation of mass and engineering principles and follow a gray-box approach. Economic decision rules are based on the assumption that when individuals are aggregated into firms, their emergent collective behavior can be described as rational. While these “rational” agents may seek to make economically optimal decisions, their ability to do so is limited by an imposed bounded rationality. For instance, agents do not have perfect information of the entire system, but act and react based on the local, limited information available to them.

The combination of an agent’s state and its decision rules gives rise to the agent’s actions, which in the models described here take the form of transactions with other agents. Just as an agent’s state and decision rules have both physical and economic aspects, transactions between agents consist of both a physical component (transfer of mass/energy) and an economic component (formation of contracts and transfer of assets). As the simulation progresses, these transactions give rise to a network structure. This structure is not predefined, but emerges as a result of the combined interactions amongst all agents. As with any modeled system, the networks in these cases have clear boundaries. The relationship of agents with the world beyond these boundaries is accounted for by their interactions with a set of two agents - an “environment” agent and a “world market” agent - each which represents certain aggregate aspects of the external world.
Case Description  This model [25, 26] describes the evolution of a global network of copper and aluminum production over a 50-year period under different global development scenarios. The focal point of the model is the evolution of a production network under different agent decision styles, different global economic conditions and different metals use cases. The main evaluation criterion for the evolved production networks is their environmental profile, which includes energy use, virgin materials use and total generated waste.

Model setup  Only the extraction and production stages of copper and aluminum life cycles are modeled, and the remaining production stages (i.e., manufacture & consumption as well as disposal & recovery), international and national institutions, and the dynamics of the physical environment are not taken into consideration. The main difference from the general model setup described above is that there is a pool of alive but inactive agents that observe both world market and cluster conditions. When sufficient demand is present, the inactive agents can decide to invest in a suitable technology. When the conditions worsen, they can decide to stop production.

Agents that want to invest make their investment decisions by first checking the supply/demand ratio of a technology’s reference products. In the case that multiple technologies demonstrate suitable S/D ratios, the agent will perform a Multi-Criteria Analysis, comparing technologies on the basis of net present value, internal rate of return, use of secondary material, generated wastes, generated emissions and energy use. Weights of these criteria are determined by the agent’s investment policy, for which there exist four options. The first policy option is ”Towards sustainability”, which is characterized by strong environmental regulation, high promotion of recycling and energy saving. The second is ”Laissez faire”, which includes weak environmental regulation, low promotion of recycling and energy savings. Third is the ”Cleaner is better” policy option, characterized by strong environmental regulation, low promotion of recycling and energy savings. The final policy option is ”Towards less extraction”, which includes weak environmental regulation, high promotion of recycling and energy savings.

For this case, the world market is defined as a dynamic actor with its own logic. It is a hybrid entity, being both an agent and having system dynamics-based behavior. The world market agent represents aggregated global metal consumption while also performing the role of exchanges like the London Metal Exchange. It sets the demand and market price of goods in the simulation. Here it is assumed that the demand of every good grows at a rate proportional to global GDP growth. Demand for copper and aluminum are set up to emulate trends where one metal is demanded as a substitute for the other.

Experiments and results  Experiments in this case tested the influence of different types of policies on the evolution of the metals production and recycling network. Different types of metrics were defined to measure aspects such as total virgin material used, total waste generated and cluster capital. For the sake of brevity, in figure 2 we present the total scrap metal used under two different policies over time. 4000 model runs over 50 time steps are plotted, and their scrap use values at each time step are plotted as a box-and-whiskers plot. Figure 2(a) presents the model runs under the “Towards sustainability” policy. Figure 2(a) presents the model behavior under the “Laissez faire” policy.

The main observation is that there is very little difference between different policies. The average of the scrap metal metrics has a relatively flat profile, except for a number of outliers,
occurring at certain parameter settings, in which a large amount of scrap is used.

(a) Towards sustainability policy. Y axis 0 - $1.7 \times 10^8$
(b) Laissez faire policy. Y axis 0 - $2.2 \times 10^8$

Figure 2: Total scrap metal used over time, 5000 experiments, policy 1 and 2

Domain-Specific Insights

The future trends are very robust across the tested world market scenarios. We do not observe radical changes over time, only outcome drift caused by the randomness of the model. There are two main issues constraining the evolutionary patterns of the model. First is the economic shortsightedness of the agents, and the second is the limited diversity of technologies available.

One of the metrics of the model that we measured was the cluster capital, which represents the sum of the assets of all the agents in the simulation. In all of the simulation runs, we observed that after a rapid increase in the cluster’s assets, the system starts to shrink, almost returning to its starting point. As the market prices increase over time, and because of the policy bias towards using recycled metal, the cluster starts evolving away from primary production. Expensive primary producers go extinct. This affects the total cluster capital negatively. The relatively strict and short-term NPV/IRR driven decision-making does not allow the agents to reinvest in expensive primary production, but instead they keep on investing in recyclers. This causes the overall collapse of the network. In order to avoid this lock-in, the agents would need to have decision-making processes that are able to examine much longer time scales and avoid local minima. Using NPV/IRR is already an improvement over previous models, in terms of longer time planning, but it is not enough in a world where the market prices are volatile and investments are very large.

Another observation was that the diversity of technologies to invest in is rather limited, so no major shift in network structure is possible. Such a shift would allow the cluster to adapt to new environmental conditions and survive. Given the current diversity, that is not possible, and the cluster collapses.

Mobile phone recycling

Case Description

The second case investigates the material flow dynamics associated with metals in mobile phones. Whereas the previous case highlighted metal production networks, the focus here is on product-level processes that impact the degree to which valuable metals are either leaked
to the environment or maintained within the network via recycling and reuse. The aim of the modeling exercise is to gain insight into the dynamics of global mobile phone flows and an understanding of how micro-level (agent-level) adjustments can lead to greater cyclicality of metal flows at the emergent system level. Use of agent-based modeling in this case enables the structure of metal/product flows to emerge through the interactions of agents rather than requiring that it be defined at the start.

Model setup

For the purpose of this investigation, mobile phone flows are assumed to consist of the processes illustrated in Figure 3(a). Refurbishing here refers to the repair and upgrading of nonfunctional mobile phones in preparation for reuse by consumers.

Underlying this setup is a simplifying assumption that mobile phones are composed only of gold, copper, silver and palladium. In other words, the manufacturing of mobile phones involves the transformation of a defined amount of these metals into a mobile phone, and metal recovery involves the opposite. Mobile phones in the model are described as discrete entities with a set of properties such as condition, age, functionality, metal content, etc. In processing mobile phones, agents adjust or reference these properties. For instance, a consumer agent might transform the condition of a phone from “new” to “used”. Metal recovery agents reference the metal content of a mobile phone in transforming it into a continuous flow of metals.

Just as actors in the real mobile phone life-cycle may be able to perform several of the processes specified above, certain agents in the model have the capability to modify the characteristics of a mobile phone in multiple ways. For instance, retailers of mobile phones in the model may collect used phones from consumers in addition to selling them new phones, and refurbishers can test and disassemble mobile phones in addition to repairing them. Thus, agents are not necessarily representative of single processes, but of sets of processes that more accurately reflect the actions of real-world actors (see Figure 3(b)).

Figure 3: Processes/flows in the mobile phone life-cycle and their translation into agents

As in the previous case, evolution in the model is driven by the purchasing and investment decisions of agents. Aside from consumers, all agents make purchasing decisions to maximize their expected profit. Likewise, decisions to invest in new technologies are driven by an analysis of profit potential in the current market.
Experiments and preliminary results

Experimentation with this model is currently ongoing. These experiments involve simultaneously adjusting various parameters in the model, and observing the impacts on the emergent system structure and its dynamics. Parameters to be adjusted include: market prices of mobile phones, metal prices, mean lifetime of mobile phones, mean use time of phones, willingness of consumers to purchase refurbished phones, price offered to consumers by collectors of mobile phones, and the average level of motivation of consumers to use proper collection pathways.

During the experimentation process, data will be collected that will enable us to paint a precise picture of the system’s structure and dynamics at each set of parameter values. Indicators such as the flows of mobile phones and metals to the environment, the stocks and assets of agents, and the quantity and quality of transactions amongst different types of agents at each timestep will be used to gain insight into the degree to which a given set of parameter values affects the cyclicality of metal flows and the dynamics that underlie it. Figures 4(a) and 4(b) show some outputs from an early version of the model. The diagram on the left shows a typical network, with the stocks of the different types of agents represented as shaded circles, and transactions between agents represented by arrows. The chart on the right shows the number of mobile phones in the stocks of each agent type during the duration of a simulation.

![Diagram](image1)

![Chart](image2)

(a) Emergent structure of the recycling system  
(b) Number of phones in stock of each agent type

Figure 4: Preliminary model outputs

Domain-specific insights

Leakage of metals to the environment has not only to do with the efficiency of manufacturing and metal recovery processes, but also with interactions throughout the entire product chain. It is expected that the model presented in this case will help to offer insights into how the flow system dynamics of metal-containing products can be affected to encourage greater cyclicality of use and reduced leakage to the environment. Agent-based modeling is an especially valuable tool for this purpose because it allows us to connect the actions and decision-making processes of specific actors with the system’s dynamics and its emergent structure. While mobile phone flows are the focus of this particular investigation, it is expected that the methodology can be adapted to study the flows associated with other metal-containing products as well.
Conclusions

The main conclusion we the readers should take away from this paper is that Agent Based Modeling is a useful tool for the metal community. The presented case studies offer an insight into the types of problems that can be examined and the types of insights that ABM can offer. Our work in other domains [27] offers exciting possibilities in extending the models of metals production and consumption with, for example Life Cycle Assessment, allowing for full environmental impact assessment of metal systems, providing us with insights in dynamic linkages between technology, economics and environmental impact. Given that the authors are not metals experts, we are actively seeking collaborators to broaden the scope of our models, to further improve the specific details and contribute to answering relevant questions in the metals domain.

References


