Tracing the Computer System Supply Chain

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Abstract

Computer systems depend on complex, geographically distributed supply chains, which generate both economic value and environmental impacts. The complexity of these networks can create a disconnect between where value is realized and where environmental burdens occur. In this paper, we use the economics framework of input-output analysis to quantify this disparity. We find that while majority upstream demand associated with computer system manufacturing is concentrated in a few high-income countries, production and resource extraction predominantly occur elsewhere.

1 Introduction

Computer systems are supported by elaborate global supply chains. Analyzing the monetary and environmental flows in these supply chains can reveal how production and consumption create economic value for some regions while imposing environmental costs on others. One way to systematically capture these interactions is through input-output tables, which record the inter-dependencies between industries within an economy, first developed by Wassily Leontief in 1930 [5]. Multi-Region Input-Output (MRIO) tables combine input-output tables from multiple countries to model economic interactions on a global scale. These tables can be further linked to environmental data such as GHG emissions, allowing the quantification of environmental flows alongside economic transactions [7].

In this paper, we employ the EORA MRIO database [3, 4] to map the manufacturing of computer systems, including intermediate products such as computer components, electronic devices, and semiconductors, through the upstream global supply chain. Using this database, we track monetary flows and environmental footprints for computer system manufacturing, including GHG emissions (in kt CO_2 eq) [1, 2] and material extraction (in t) [9] across different regions.

We find that global demand for computer systems is concentrated in a small number of countries, while the production needed to meet this demand is distributed across many regions. GHG emissions associated with this production are largely generated in a subset of regions, particularly in Asia, indicating that environmental burdens are often carried by countries other than the main consumers. A similar pattern appears for material extraction: although demand is concentrated in high-income economies, resource extraction occurs across countries in South America, Africa, and Asia. These patterns highlight the uneven distribution of economic benefits and environmental impacts along the global upstream computer system manufacturing supply chain.

2 Background and Methodology

The Input-Output (IO) tables are based on actual economic data, and are constructed from several interrelated matrices that together describe an economy's production and consumption structure [8]. Here we illustrate the IO analysis framework with a simplified case of a single-country IO table representing an economy with n sectors. The matrices are:

- $Z_{n \times n}$: inter-industry transaction matrix, each element z_{ij} is the monetary flow from sector i to sector j.
- $Y_{n \times k}$: final demand matrix, representing demand for goods and services by households, governments, and exports etc. (denoted by k) for each sector.
- $V_{p \times n}$: value-added matrix that captures wages, profits, and taxes etc. (denoted by p) generated by each sector.
- $X_{n \times 1}$: gross output vector, where each element x_i is the gross output of sector i combining both inter-industry use and final demand.
- $Q_{e \times n}$: environmental extension matrix (satellite account), with e rows representing different environmental flows (like GHG emissions) across sectors.

In the IO table, the total value of inputs to each sector equal the total value of its outputs to other sectors or final demand, that is $X = Z + Y$. The Z matrix shows a sector's direct demand, measured by how much money flows from all other sectors (rows) to the sector of interest s (column). However, supply chains are typically multi-layered, and many sectors contribute indirectly to sector s for instance. These upstream contributions constitute the indirect demand.

To get the total demand (direct and indirect) for a given sector, we first calculate the technical coefficients matrix A, which expresses the inputs from each sector that are directly required to produce one unit of output in every sector, or $A = Z.\hat{X}^{-1}$; where $\hat{X}^{-1} = diag(X)$. Now, since $X = Z + Y$, we can substitute $Z = A.X$ to get $X = A.X + Y$ or $X = (I - A)^{-1}.Y$. This is the Leontief inverse $L = (I - A)^{-1}$, which captures both the direct demand (the inputs a sector receives immediately from other sectors) and the indirect demand (the upstream inputs required by those supplying sectors) needed to satisfy final demand. The sum of direct and indirect demand gives the total demand exhibited by a sector. Using L, the total output to satisfy a given final demand vector Y can be calculated as $X = L.Y$.

IO tables can be extended with the environmental extension matrix Q, that records environmental flows per unit of sector output. Environmental impacts can be attributed using either production-based accounting, which assigns impacts to the location where goods are produced ($F_{prod} = Q.X$); or consumption-based accounting, which assigns impacts to the location where goods and services are ultimately consumed,

(a) Total Demand (1000 USD) **(b)** GHG Emissions (kt CO_2 eq) **(c)** Total Ore Extraction (t)
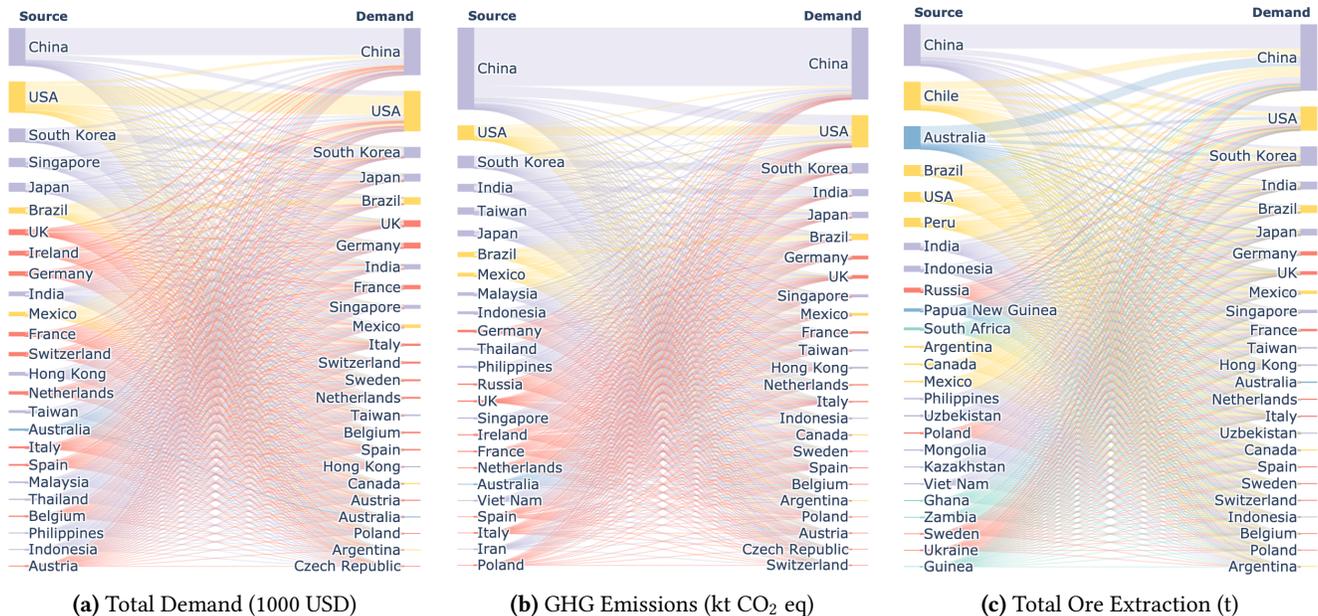
Figure 1. Upstream economic and environmental flows associated with computer system manufacturing.

capturing the total upstream footprint along the supply chain ($F_{cons} = Q.L.Y$).

Using this IO analysis framework, we analyze the monetary and environmental flows associated with computer system manufacturing using the Full EORA dataset [3, 4, 6], a state-of-the-art global MRIO dataset covering 15,909 sectors across 190 countries. Our analysis is based on the year 2017 (latest available year in open-source version). For our analysis, we include all sectors related to semiconductor manufacturing, electronics manufacturing, and computer system production across regions, resulting in 65 unique sector–country combinations. We quantify the upstream production associated with computer system manufacturing, which captures the total demand (direct and indirect) induced across all sectors. EORA also provides several environmental extension accounts, of which we focus on two indicators: total GHG emissions (in kt CO_2 eq), and total ore extraction (in metric tonnes), to calculate consumption-based footprints.

3 Results and Future Work

The results of our analysis are shown in Figure 1. Source countries represent suppliers along the global supply chain (including indirect upstream contributors), while demand countries represent final consumers. Terminals on both sides are colored by world region (Africa, the Americas, Asia, Europe, and Oceania), and the top 25 source and demand countries are displayed. Figure 1(a) shows the total demand associated with all the sectors corresponding to computer system manufacturing. Demand is highly concentrated in a small number of countries, most notably China and the US, along with several European economies, whereas supply is more geographically dispersed, with major contributions from China,

the US, South Korea, Japan, and other Asian economies. The final demand is concentrated in a few regions, while the upstream production is more globally distributed.

Figure 1(b) shows consumption-based GHG emissions associated with computer system manufacturing (in kt CO_2 eq). Emissions attributed to source countries reflect production that occurs in response to final demand in the consuming countries. The source side is dominated by Asian economies, which may partly reflect the concentration of energy and manufacturing-intensive activities in regions with more carbon-intensive electricity mixes. The carbon-intensive stages of the supply chain are outsourced to other countries, while final demand remains concentrated in high-income economies. For example, the US exhibits substantially higher emissions on the demand side than on the source side, indicating that a large share of emissions due to US consumption occurs outside its borders. Figure 1(c) presents consumption-based material extraction, measured as total ores extracted (in metric tonnes). Final demand is concentrated in a small set of countries, including China, the US, South Korea, and Japan, while ores are sourced predominantly from South American, African, and Asian economies, reflecting the geographic separation between material extraction and final consumption.

These figures reveal a clear mismatch between where monetary value is generated and where environmental burdens occur along the supply chain. Despite their high-level aggregation, IO models can guide future work by pinpointing supply chain stages and regions where interventions could reduce environmental impacts and improve equity in computer systems manufacturing.

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