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The carbon footprint of machine tools and metal working machinery in U.S. manufacturing

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Abstract

Recent research suggests that one-third of the global supply of metals is used to produce machinery and industrial equipment (ME). ME production causes 8% of global greenhouse gas emissions. Yet, our understanding of how much different types of ME contribute is limited. While the energy use needed to operate machines usually enters life cycle assessments, the production of the machines is often neglected, mostly because data is lacking. Here we explore the use of detailed economic input-output data for the United States (USEEIO) to produce cradle-to-gate life cycle inventories for machinery for material handling and metalworking, machine tools, dies, fixtures, and industrial molds. The cradle-to-gate GHG emissions of the investigated machinery were 38 million tonnes CO_2e (0.5% of US emissions), compared to 330 Mt for all ME. Materials contributed 46-63% to the carbon footprint of the ME in question, the production of electricity and fuels used in production processes other than materials production contributed 13-28%. Important uses of ME as capital products were in the manufacturing of vehicles, refining, and metal industries. Important uses as intermediate inputs were oil and gas production, mining, as well as manufacturing and commercial structures. This manuscript demonstrates the feasibility of using detailed input-output tables for life cycle inventory modelling of the production and use of ME.

Keywords: Sustainable manufacturing, circular economy, life cycle assessment, industrial ecology, climate change mitigation, resource efficiency

1. Introduction

Machines are everywhere but in sustainability analyses. Machinery and equipment (ME) are tools humans use either for productive purposes or to provide services directly to consumers, alongside buildings and infrastructure and vehicles which serve in a similar manner[1–3]. ME embodies technology. Over its lifetime, ME enables production and prescribes the production recipe and the required inputs. ME is constituted from materials and produced by manufacturing. In 2020, the manufacturing of ME used 30% of global metal output and caused 8% of global greenhouse gas emissions (GHGE)[4]. The Paris Agreement[5] challenges manufacturers to achieve net-zero GHG emissions for both the operation and the production of ME. Yet, machinery stocks are likely to grow as developing countries catch up with industrialized ones and countries respond to labour shortages resulting from their aging populations. Figure 1 compares the stocks of ME available to different populations across the world. It indicates a substantial catch-up may happen.

Nomenclature

ME	machinery and equipment
GHGE	greenhouse gas emissions
LCA	product life cycle assessment

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Little sustainability research has investigated the overall importance of ME. Few life cycle assessments (LCAs) exist for ME. LCAs of manufactured goods rarely consider the use of ME as an input. There are few if any analyses on how to reduce the environmental impacts of ME. ME, however, appears in macro-level sustainability studies as a use of metals and a product of economic activity.

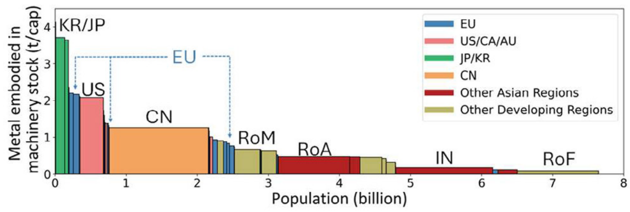

Figure 1: Metals used to produce the stock of machinery and equipment accumulated in different countries and regions as of 2019. The y-axis shows the per-capita stock levels. Regions include Europe (EU), the United States, Canada, and Australia (US/CA/AU), Japan and Korea (JP/KR), China (CN), India (IN), other Asian countries (RoA), other Middle Eastern countries (RoM), and other African countries (RoF). The figure highlights low ME levels in India and Africa (RoF) compared to industrialized regions. European countries show relatively dispersed per-capita ME stock. Data and figures are updated based on our previous study[4], excluding transport equipment and unspecified manufactured products.

1.1. The special role of ME

As a capital good, ME is not consumed in the production process, but used over many years. It is the stock of ME (Figure 2) that serves production, the inflow of new ME serves to expand the stock and replace retiring ME. ME is hence part of the stock-flow-service nexus[6]. ME is even more special, as ME is needed to produce ME, buildings and infrastructure, vehicles, and a low-carbon energy system. It is the capital good to make other capital goods (Figure 2).

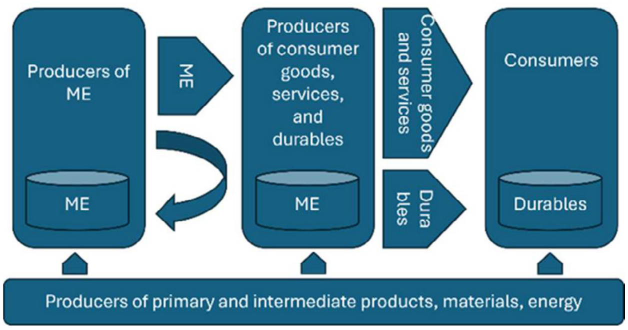

Figure 2 Scheme indicating the role of machinery and equipment (ME) in the provision of products and services to consumers. It indicates that demand for ME is likely not steady and linked to consumption in complicated ways.

There are several research streams that provide insights into the role of ME in sustainability. A key challenge in ME research is the product heterogeneity compared to buildings or transport equipment. ME varies significantly across industries, with many different types in use. As a result, research approaches are often either very broad, using macro models that treat ME as one or a few sectors, or very narrow, focusing on life cycle analyses of specific ME types.

In most of sustainability analyses covering ME, it is there because the entire economy is depicted, and it is not always specified and rarely explicitly analysed. Material flow analyses provide a top-down picture of material flows. While they capture the production and use of materials, only recent analyses are resolved enough to address the use of materials for ME production. According to Wiedenhofer and colleagues[7], by 2016, 6 billion tons of ME had accumulated. Most of this ME consisted of metal. Similarly, research on metal use has identified ME as one key application[8,9]. It suggests that material efficiency is an important mitigation strategy that also applies to ME. One study of parts[10] suggests that only 10% of metal used during production is necessary for the function of the part. 40-60% of metal is removed or spilled during the production process. Overspecification of parts and the failure to us material properties to the limit accounts for the remainder. Previous studies of environmental impact

Top-down quantifications of environmental footprints with input-output analysis have also identified machinery and equipment. Our research team has contributed to analysing the role of manufactured capital in carbon footprints. We found that including capital increases assessed carbon footprints by between 20% (food) and 200% (telecoms)[11]. Recently we analyzed ME using the well-established EXIOBASE global multiregional input-output database[4]. Like other capital-focused analyses, it shows a recent rise in the importance of capital goods given China's rapid economic development and high levels of investment (ca. 40% of GDP compared to 15-25% in other countries).

Life cycle assessments could be found only for few of the types of ME considered in this study (see next section). Regarding material handling systems, a studies on cranes[12] suggests that operations was the most significant phase of the life cycle. A study compared conveyor belts and trucks in mine operations[13], finding that various impact categories favoured one or the other. One study on designs of a welding robot compared two different welding technologies, identifying a favorite[14]. A review[15] summarizes findings from various approaches to studying machine tools, many of them conceptual.

1.2. Scope of this work

This work aims to investigate to what degree input-output tables can be used to describe (a) environmental footprints of producing ME at a more granular level than was achieved in Jiang and colleagues[4], and (b) to what degree they can provide information on the use of ME by other sectors. Like a few other countries, the United States benchmark tables offer more detail with 400 sectors described. For 2007 and 2012, capital use tables were constructed[16] and their contributions to footprints were analysed[17]. All ME are grouped into 64 sectors. Here we analyse the role of following: 'Industrial mold manufacturing' (NAICS 333511), 'Special tool, die, jig, and fixture manufacturing' (333514), 'Machine tool manufacturing' (333517), 'Cutting and machine tool accessory, rolling mill, and other metalworking machinery manufacturing' (33351B), 'Material handling equipment manufacturing' (333920), and 'Other general purpose machinery manufacturing' (33399A), see https://www.census.gov/naics/ for a more detailed specification. We address both the production and the use of ME. For the production, we separate out the contribution of the use of capital, energy, and materials, and distinguish these from direct emissions occurring in the production of ME and those arising from producing other inputs (components, services).

2. Methods

The USEEIO with capital extensions for the year 2012 was used[16,18]. The hypothetical extraction method[19,20] was used to identify materials, energy, and capital inputs. Benchmark IO tables with the desired level of detail are published only every 5th year and the most recent data is for 2017, however, no capital use matrix exists for that year. The calculations were coded in Python using Numpy and Pandas.

2.1. Materials, energy, and capital contribution to carbon footprints

Following matrices were used: The input-output coefficient matrices for intermediate A and capital inputs A_K; the final demand matrix Y specifying final demand by households, government, and for investment, as well as imports, exports, and change in inventories; the greenhouse gas emission coefficients per sector, T; and the global warming potentials expressing the contribution of gases to radiative forcing over 100 years, π. I is the identity matrix and i is a column vector of 1s. The multipliers, expressing cradle-to-gate emissions per unit product value, were calculated using the standard Leontief demand model

$$m = \pi T L \tag{1}$$

where $L = (I - A)^{-1}$ is the Leontief inverse. These emissions do not include the emissions that were associated with the use of capital in the process. Multipliers including capital use were also calculated, $m_{I+K} = \pi T (I - A - A_K)^{-1}$. The contribution of using the capital stock of machinery and equipment was then calculated as $m_K = m_{I+K} - m$.

In the hypothetical extraction approach, we identified intermediate input of target products A^o and separated this from all other inputs $A^* = A - A^o$. Based on the Leontief price model, the contribution of target products to the carbon footprint of other products is determined

$$M_T = \widehat{m} A^o L^* \tag{2}$$

We chose all energy carriers and materials as target products, for which we will have non-zero row-entries reflecting the contribution of each of the energy carriers and materials to the carbon footprint of all products in the economy. We added those reflecting energy to obtainm_E and those reflecting materials to m_M. Finally, the direct emissions during the production process of each product are given by $m_D = \pi T$ and the remaining emissions from the production of intermediate inputs not related to their purchase of energy or materials are given as $m_I = m - m_E - m_M - m_D$. Most of these emissions will be from the combustion of fuels in intermediate production processes. We hence created a matrix of multiplier contributions, $M = [m'_E; m'_M; m'_D; m'_I; m'_K]$. Here, the hyphen indicates a transpose i.e. that we have individual multiplier vectors as row vectors. The semicolon that they are stacked on top of each other.

2.2. Intermediate and final demand for ME

We conducted a separate hypothetical extraction of ME to identify the intermediate demand for ME by other sectors for domestic production. This was given as $\xi_d = A^o L^* y^*$, where y^* is the sum of final demand columns describing domestic consumption and investment. We also identified the domestic final consumption of and investment in ME, Y^o. The sum $\xi_d + Y^o i$ is then the domestic intermediate and final demand for ME excluding intermediate demand for ME production, i.e., avoiding double counting.

The carbon footprint (cradle-to-gate assessment) of specific machinery and equipment (Fig.3) was then calculated picking the corresponding columns of

$$\Delta = M \hat{\xi} \tag{3}$$

2.3. Use of ME by different production activities

In the previous section, we described the final consumption of and investment in ME in a given year. That year, the same type of ME is used for production purposes. However, investment in the ME used for production has, for the most part, occurred in the past. The amount of capital product used for productive purposes is reflected in the matrix A_K. This matrix hence contains information where specific ME is used. We calculated a matrix representing the contribution of each capital product to the carbon footprint of each output in the economy

$$\Delta_K = \widehat{m_{I+K}} A_K \hat{x} \tag{4}$$

and then examined the rows representing the ME products in question. Results were used to identify the industries with the largest demand for the ME products and to calculate the contribution of those products to the total carbon footprint of the using industries. More details of the calculations are noted in our previously papers[19,20].

3. Results

3.1. Cradle-to-gate GHG emissions of ME

The average carbon footprint multiplier for the selected six types of ME was 450 tonnes CO_2e per million US$ of machinery, although it ranged from 370 to 500 t/M$ (Table 1). The depreciation of capital goods used in ME production caused on average 11% of the emissions. We did not further investigate what contributed to these emissions of capital. The production of materials contributed 55% of the footprint. Providing energy used in the manufacturing process of ME, i.e. apart from producing materials and capital, caused 19%. Manufacturing components and providing other inputs caused 12%. Direct emissions during manufacturing of ME contributed, on average, only 3% to the total footprint of the investigated ME.

Table 1: Carbon footprint multiplier for selected tools, machinery and equipment, demand, and cradle-to-gate contribution to the carbon footprint of different types of input.

Machinery type	Share of carbon footprint contributed by Energy	Materials	Other	Direct	Capital	Multiplier tCO2e/M$	Demand G$
Industrial molds	28%	46%	11%	6%	9%	494	7.2
Tools, dies, fixtures	24%	54%	10%	4%	9%	374	8.5
Machine tools	19%	53%	13%	3%	11%	401	12
Metalworking	24%	50%	10%	4%	11%	403	9.7
General purpose	13%	62%	11%	2%	11%	501	30
Material handling	21%	50%	14%	4%	12%	425	19

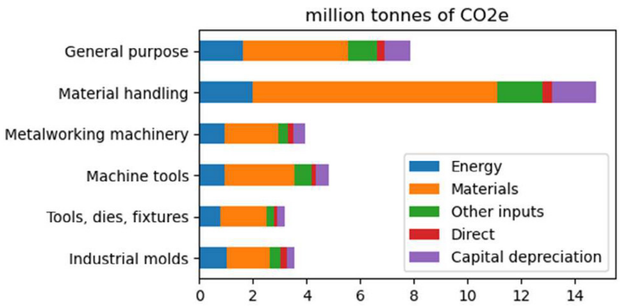

Figure 3: Carbon footprint of specific machinery purchased as intermediate inputs, for final consumption, or as investment products (categorized under Scope 3 emissions) in the US in 2012. Results are based on the modelling estimates from USEEIO[16,18].

The demand for the investigated metal working and manufacturing machinery and equipment, including machine tools, was 86 billion US$ (Table 1). This demand includes intermediate demand (25 bln$) which is consumables, and investment into new equipment (60 bln$). By comparison, the depreciation (consumption of fixed capital) of existing ME of the same types was 45 bln$.

Producing the demanded ME caused GHG emissions of 38 million tonnes of CO2 equivalent (MtCO2e). Material handling equipment was most important with over 14 MtCO2e, followed by general purpose machinery, machine tools, metal working machinery, industrial molds, and finally, tools, dies, and fixtures (Figure 3).

3.2. Use of machinery and equipment

The machines, equipment and tools in question were used by a great many industries. As indicated above, ME produced in previous years are used in the form of capital (45 bln$) and ME produced in the current year are used as intermediate inputs, or consumables (25 bln$).

The use as capital is displayed in Figure 4. The most important use in terms of GHG emissions was in light truck and utility vehicles (UVs) manufacturing, followed by petroleum refineries, the iron and steel industry including ferroalloys, scientific research and development, and automobile manufacturing. Only in the first industry was the contribution of this ME to the carbon footprint of the industry more than 1 $MtCO_2e$.

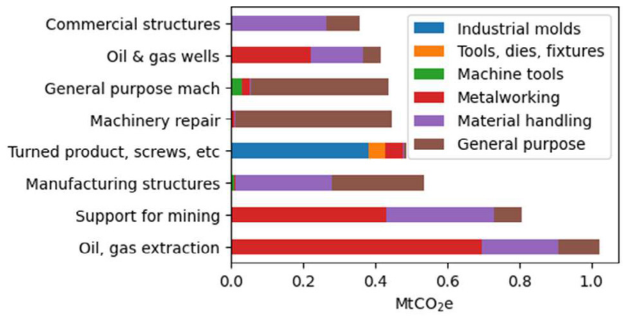

Figure 4: Contribution of the use of machinery and equipment capital to the carbon footprint of products, ranked by the size of such contribution. Abbreviations: UVs = Utility vehicles, R&D = research and development, non-Fe, non-Al metals = smelting and refining of nonferrous, non-aluminium metals, ONDG = other non-durable goods.

The use of ME as intermediate inputs or consumables differs substantially from that as capital product (Figure 5). Here, oil & gas extraction and other support activities for mining, which includes exploration, are the largest users, using predominantly metalworking machinery and material handling equipment. Producing manufacturing structure (i.e. factory buildings) and commercial and office structures requires material handling and other general purpose machinery. Turned products and screws, nut, and bolts rely on industrial molds. General purpose machinery is required to produce general purpose machinery, which potentially reflects the input of semi-finished parts from the same sector and is such more an artefact of the input-output accounts, which is based on surveys of trades among firms rather than representing inputs from other industries.

We also investigated the contribution of the ME in focus to the carbon footprint of products. The contribution to the average product is only 0.4%. However, some products stand out. For example, the ME contributes 10% to the carbon footprint of relay and industrial control manufacturing, 5% to turned products, screws, nuts, and bolts, and 3% to semiconductor manufacturing (Table 2).

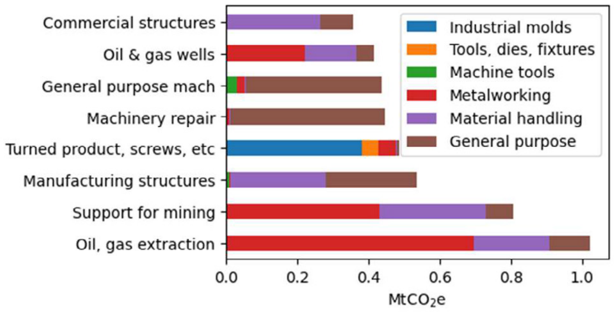

Figure 5: Contribution of the intermediate input of identified ME to the carbon footprint of sectors, ranked by size of the contribution. Top 8 using sectors are shown.

Table 2: Contribution of the selected machinery, equipment, and tools to the carbon footprint of industries, ranked by share.

Industry	Share ME
Relay and industrial control manufacturing	10%
Turned product and screw, nut, and bolt manufacturing	4.9%
Special tool, die, jig, and fixture manufacturing	4.5%
Commercial and industrial machinery and equipment repair and maintenance	3.9%
Semiconductor machinery manufacturing	3.4%
Ammunition, arms, ordnance, and accessories manufacturing	2.4%
Manufacturing structures	2.4%

4. Discussion and conclusions

We have shown here that it is feasible to use the USEEIO to determine the carbon footprint of machinery and equipment for 65 types of machinery and equipment. We have used six types of ME to illustrate this possibility and explore what type of results we can get. We have also shown that the transaction matrix and the capital flow matrix of the USEEIO[16] can be used to determine where the investigated ME is used and to quantify how this ME contributes to the overall carbon footprint of produced products.

The approach is feasible and can easily be extended to other types of machinery. Of course, other ME will contribute to the footprint of other products. For example, Heating, Ventilation, and Air Conditioning (HVAC) systems – the most important ME category in terms of their cradle-to-gate GHG emissions – will contribute to buildings. Agricultural machinery to food products.

The approach can be used for other types of environmental impacts, given that the USEEIO has been extended to cover 13 types of environmental impacts[21]. Further, USEPA has published a new USEEIO using the 2017 benchmark IO tables from the Bureau of Economic Analysis. The integration of capital accounts to this new dataset for 2017, however, is still outstanding. It should be noted that, while the US government publishes the detailed input-output tables every five years, the capital flow tables were produced for only for two years by our research group, combining information from many individual US statistical sources. There is no mechanism in place to update these tables.

In life-cycle assessment, such cradle-to-gate data for machinery impacts can be used like any other cradle-to-gate data as an input in the construction of life cycle inventories. This is also called the systems process. If the analyst does not know the utilization and price of the ME in question, industry-averages from USEEIO can be used as demonstrated here. Of course, current numbers reflect the status over a decade ago. We do not know how much things have changed. If the LCA analyst is happy to use numbers from 2012, because they might reflect the age of the actual machinery in use pretty well, there might still be a need to adjust the capital use numbers and to account for inflation. Another option to update the numbers is to work with the 71 sector resolution published annually by the US Bureau of Economic Analysis, to either adjust the detailed benchmark tables or to derive adjustment factors for the use of energy and materials and the associated emissions which can then be applied to the numbers presented here.

Another option to update the current modelling and integrate it better into the standard process life cycle inventory praxis would be to estimate unit process proxies. We would quantify the materials and energy carriers used in physical terms and then replace the 2012 values with more current data. Given the large importance of materials and energy carriers, this would be a significant advance. Such approximated unit-process inventory data would also be useful for representing machinery and equipment in integrated assessment models to consider ME in the development of climate change mitigation scenarios. We have pioneered such an approach for electric machinery and equipment used in electricity generation and distribution[22,23].

Carbon footprint estimates of individual products based on input-output models have substantial uncertainties[24]. A fundamental issue is that national statistics invariably reflect a wide collection of products within the same classification; these can be complete machines, parts of machines, or services provided by the machine-building industry. In one category, we have cutting and machine tool accessory, rolling mills, and other metalworking machinery. A life cycle assessment of a particular rolling will give a more precise estimate of the life cycle inventory of that machine. Many LCAs and information on production volumes are required to provide a more accurate estimate of the entire category based on a bottom-up approach. Engineering-based assessments of particular ME are also needed to understand opportunities for emission reductions.

A good starting point for research into the mitigation of machinery-related GHG emissions is the insight that more than half of the emissions from ME production are associated with materials. Material efficiency and circular economy measures [8,9], in addition to decarbonization of material supply, will go a long way in reducing these impacts. Recent findings on the potentially large reductions of metal use in making parts are relevant for ME[10]. The second target should be the energy supply to ME production. Given the importance of electricity, the decarbonization of electricity production, which is already underway, will be important. In the medium run, material supply will have to be decarbonized. While technologies are available, they require substantial investments and take time to implement. In the current decade, material efficiency, energy efficiency, and electrification carry highest promise for reducing the GHG emissions associated with the production of machinery and equipment.

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