Life-Cycle Cost of Manufactured Goods: A Case Study in US Ground Passenger Transportation

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Abstract: National governments invest in research and development to advance efficiency and spur economic growth. There are, however, few studies that identify where investments will have the largest possible return on investment. This lack of research can result in the funding of investments with suboptimal returns. Initial research in this area has focused on examining production costs; however, to identify high-return areas of research, efforts need to be taken further to include both the production and use of a product. This paper examines the life-cycle cost of passenger ground transportation as a proof of concept to identify those items that have both a high cost and high environmental impact. Public research that focuses on these items has the potential to be more economical than other areas. This paper uses US input-output data from the US Bureau of Economic Analysis, data from the American Time Use Survey, and environmentally extended input-output data to examine the supply chain for production and use of ground transportation equipment. This paper is unique in that it identifies the costs, some of which are not documented in GDP (i.e., uncompensated time use), along with the environmental impacts of producing and using a class of manufactured goods. The Pareto principle, which posits that roughly 80 % of a problem is due to 20 % of the causes, is utilized for targeting specific efficiency solutions. Those supply chain entities that are above the 80th percentile for both financial costs and environmental impacts are identified. The robustness of this identification is examined using Monte Carlo techniques. Forty-three supply chain entities were identified as being above the 80th percentile for cost, measured in value added, and environmental impact with six being above the 95th percentile for both.

1. Introduction

As illustrated in Figure 1, governments seek to advance efficiency in the economy by reducing inputs and negative externalities (represented in red with down arrows indicating a decrease), such as environmental impact, while increasing output and product function (represented in green with up arrows indicating an increase). The result is an increase in the quality and quantity of production at lower per unit costs and environmental impacts. These types of advancements facilitate sustained economic growth that increases average income.[1] On their own accord, firms pursue efficiency improvements that increase profit; however, there are limited incentives for a firm to pursue activities in which they cannot sufficiently capture enough of the benefit, such as environmental sustainability. Additionally, there are potential efficiency improvements that might not be achieved due to market failures. For this reason, governments invest in research and development to advance efficiency that results in sustainable economic growth. Unfortunately, there are a limited number of studies that identify the research areas that have the potential for having the highest return on investment. The result is that governments can often fund suboptimal investments.

Previous work by Thomas and Kandaswamy examined assembly-centric products (i.e, machinery, electronics, computers, and transportation equipment) to identify those supply chain points that accounted for a disproportional amount of the cost of production.[2] In another paper, Thomas and Kandaswamy

[1] Weil, David N. Economic Growth. United States: Pearson Education Inc., 2005. 181

[2] Thomas, Douglas and Anand Kandaswamy. "Identifying High Resource Consumption Areas of Assembly-Centric Manufacturing in the United States." Journal of Technology Transfer. 2017.

examined, at the industry level, material flow time, which is often used by manufacturers to track and improve competitiveness.[3] The same authors used input-output analysis to identify supply-chain points that consume high levels of resources, including financial and environmental resources.[4] Each of these papers focused on the inputs and/or negative externalities associated with production. This paper extends that work by examining both production and the function of a product.

With a multitude of products, processes, and activities, a holistic approach will require a systematic method to examine production and utilization. The standard categorization of industry activity combined with input-output analysis, which was originally developed by economist Leontief,[5] provides a foundation for such an approach. Input-output models are typically used to estimate the impact of a shift in demand for a good or service, but they also provide information on inter-industry activity, making such models an invaluable resource for industry-by-industry resource use within the US economy.

A frequently invoked axiom posits that roughly 80 % of a problem can be traced to 20 % of the cause(s), a phenomenon referred to as the Pareto principle.[6] This paper identifies those cost items that account for a disproportionally high level of resource consumption compared to other cost items. A method is developed and used to examine US ground passenger transportation as a case study. Passenger transport represents multiple industries each with many supply chain costs. A multi-factor approach is used to measure environmental impact and value added. Note that value added is the revenue that an establishment receives less the purchases from other establishments; thus, it is the establishment’s contribution to the cost that the consumer bears in purchasing the final product.

The purpose of this paper is to facilitate the identification of economy-wide opportunities for researched efficiency improvements in the production and use of products. Researchers are unable to identify and compare all potential research topics that impact efficiency; thus, a method is needed to create a pool of high return investments to select from. Return on investment (ROI) can be represented as:

$$ROI = \frac{Benefit\ of\ Investment - cost\ of\ Investment}{Cost\ of\ Investment}$$

Cost categories, which in this paper are classified as NAICS codes, represent similar activities occurring within one location. Additionally, a high cost, as measured in value added, primarily occurs either because of high cost processes (through labor or profit) or a high volume of production (i.e., many units); thus, an efficiency improvement in a high cost area is, likely, to have a greater potential benefit through spillover than an efficiency improvement in a low-cost area. Stated another way, high cost categories represent a potentially target rich environment of investments with a high level of benefits that can result in a high return on investment. Additionally, those production activities that have both a high cost and high environmental impact, which will be referred to as consuming a high level of resources, provide a robust opportunity for efficiency improvement affecting multiple stakeholders (i.e., citizens, consumers, and producers). Public entities, trade organizations, and other change agents that seek to maximize efficiency improvement through innovative solutions can search for potential research areas in high cost areas, increasing the likelihood of identifying high return investments. After identifying high cost/impact areas, potential research topics within those cost areas can be identified and compared. It is important to

[3] Thomas, Douglas and Anand Kandaswamy. 2017 “An Examination of National Supply-Chain Flow Time.” Economic Systems Research. http://www.tandfonline.com/doi/full/10.1080/09535314.2017.1407296

[4] Thomas, Douglas and Anand Kandaswamy. 2017

[5] Miller, Ronald E. and Peter D. Blair. Input-Output Analysis: Foundations and Extensions. Second Edition. New York: Cambridge University Press, 2009.

[6] Hopp, Wallace J. and Mark L. Spearman. Factory Physics. Third Edition. Long Grove, IL: Waveland Press, 2008. 674.

note that there are a number of factors that are relevant to choosing the most economical investments to improve efficiency. The approach in this paper is a method for examining one of those factors.

2. Methods

This paper uses input-output data and analysis to examine various aspects of the supply chain for ground passenger transportation. Business and personal expenditures on transportation are inserted into an input-output model, which estimates value added and environmental impact by industry. This is combined with an estimate of personal time use for transportation. Industries are categories of establishments (i.e., physical locations of economic activity) based on the product being produced and the processes being used. Commodities (i.e., products and services) are exchanged between industries and are also delivered to the final consumer. For a particular finished commodity, the value added from each industry and the environmental impact from each industry is estimated. The methods in this paper build on those in Thomas and Kandaswamy (2016)[7], Thomas and Kandaswamy (2016)[8], and Thomas and Kneifel (2016).[9] The analysis is examining the life-cycle cost and environmental impact of ground passenger transportation (i.e., cost and environmental impact for production, energy for use, maintenance, repair, and time use), but will look at one year to estimate it. At the national level, expenditures have relatively similar expenditures year to year. This analysis assumes that expenditures remain the same; therefore, regardless of whether one examines one year or thirty years, the relative ranking of the costs will remain the same.

2.1. Environmental Impact

The measure of environmental impact is calculated using input-output analysis combined with TRACI 2 impact categories and the Analytical Hierarchy Process to weight the categories. A description of the calculations is below.

Input-Output Analysis: The Make-Use tables are used for Input-Output analysis.[10] The model operates under constant returns to scale and thus ignores potential economies of scale. [11] The model also assumes that a sector uses inputs in fixed proportions. These issues are, typically, relevant to analyses that examine the impact of a change in demand.[12] This paper is not seeking to predict the impact of a change in demand, but rather seeks to track the total resources used for the production of particular goods; therefore, ignoring economies of scale and assuming sectors use inputs in fixed proportions has minimal impact on this analysis. This paper also uses an industry-by-commodity Input-Output format as outlined in Horowitz

[7] Thomas, Douglas and Anand Kandaswamy. “Identifying High Resource Consumption Areas of Assembly-Centric manufacturing in the United States.” National Institute of Standards and Technology. White paper. 2016.
[8] Thomas, Douglas and Anand Kandaswamy. “Improving Manufacturing Efficiency through Supply-Chain Flow Time.” National Institute of Standards and Technology. White paper. 2016.
[9] Thomas, Douglas and Joshua Kneifel. “Identifying Environmental Impact Hotspots of Assembly-Centric Manufacturing in the US.” National Institute of Standards and Technology. White paper. 2016.
[10] Miller, Ronald E. and Peter D. Blair. Input-Output Analysis: Foundations and Extensions. Second Edition. New York: Cambridge University Press, 2009. 135-138.
[11] Miller. 16.
[12] Horowitz, Karen J. and Mark A. Planting. Concepts and Methods of the US Input-Output Accounts. Bureau of Economic Analysis. September 2006. http://www.bea.gov/papers/pdf/IOmanual_092906.pdf

and Planting (2006), which accounts for the fact that an industry may produce more than one commodity or product, such as secondary products and by-products.[13, 14, 15]

An input-output analysis develops a total requirements matrix that when multiplied by the vector of final demands equals the output needed for production. The total requirements matrix is developed using the methods outlined in Horowitz and Planting (2006):

Equation 1

$$X = W(I - BW)^{-1} * Y$$

Where:

$X =$ Vector of output required to produce final demand

$Y =$ Vector of final demand

$W = (I - \hat{p})D$

$B = U\hat{g}^{-1}$

$I =$ Identity matrix

$D = V\hat{q}^{-1}$

$p =$ A column vector in which each entry shows the ratio of the value of scrap produced in each industry to the industry's total output.

$U =$ Intermediate portion of the use matrix in which the column shows for a given industry the amount of each commodity it uses—including noncomparable imports, scrap, and used and secondhand goods. This is a commodity-by-industry matrix.

$V =$ Make matrix, in which the column shows for a given commodity the amount produced in each industry. This is an industry-by-commodity matrix. V has columns showing only zero entries for noncomparable imports and for scrap.

$g =$ A column vector in which each entry shows the total amount of each industry's output, including its production of scrap. It is an industry-by-one vector.

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[13] Ibid.

[14] Miller. 184.

[15] European Commission. Eurostat Manual of Supply, Use, and Input-Output Tables. 2008 Edition. 2008. Accessed September 2016. http://ec.europa.eu/eurostat/documents/3859598/5902113/KS-RA-07-013-EN.PDF/b0b3d71e-3930-4442-94be-70b36cea9b39?version=1.0.

$q =$ A column vector in which each entry shows the total amount of the output of a commodity. It is a commodity-by-one vector.

$\frown$ A symbol that when placed over a vector indicates a square matrix in which the elements of the vector appear on the main diagonal and zeros elsewhere.

In Equation 1, a total requirements matrix $W(I - BW)^{-1}$ is multiplied by a vector of final demand for commodities Y to estimate the total output X. All variables in Equation 1 have known values in the input output data. The output X required to produce an alternate level of final demand can be calculated by altering the final demand vector from the actual final demand Y in the input output data to Y'. For this analysis, Y' has the actual final demand for assembly-centric commodities and zero for other commodities. This alteration reveals the output needed to produce only assembly-centric commodities.

Environmental Impact Categories: The TRACI 2 impact categories are each an aggregation of multiple emissions converted to a common physical unit. For example, the global warming impact category includes impacts of many pollutants, such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (NO_X), and fluorinated gases, which are converted to their carbon dioxide equivalent (CO_2e) impact and aggregated to estimate the total impact for that impact category. The environmental impacts are measured in terms of the common physical unit per dollar of output. The impact can be calculated by multiplying the output in the Input-Output analysis by the impact categories.

Impact Category Weights: Having 12 environmental impact categories makes it difficult to rank industry environmental activity; therefore, the 12 impact categories have been combined into a single environmental metric using the Analytical Hierarchy Process (AHP). AHP is a mathematical method for developing weights using normalized eigenvalues. It involves making pairwise comparisons of competing items based on a multilevel hierarchy developed by the user. The weights used in this paper were developed for the BEES software and can be seen in Table 1.[16] This paper uses 12 of the 13 impact categories for which weights were developed. Indoor Air Quality (IAQ) is excluded because it is more applicable to the design of buildings and ventilation systems rather than to manufacturing activities. The weight of IAQ is proportionally allocated to the other 12 impact categories. The final metric for each industry or industry/commodity combination is the proportion of the total impact from assembly-centric products. The percent of environmental impacts, based on the weights, are calculated using the following equation:

[16] Lippiatt, Barbara, Anne Landfield Greig, and Priya Lavappa. Building for Environmental and Economic Sustainability. National Institute of Standards and Technology. 2010. Accessed September 2016. http://www.nist.gov/el/economics/BEESSoftware.cfm.

Equation 2

$$Env_{z,Y'} = \frac{x_{z,Y'} * GWP_z}{\sum_{i=1}^{n} x_{i,Y'} * GWP_i} * 0.30 + \frac{x_{z,Y'} * Acid_z}{\sum_{i=1}^{n} x_{i,Y'} * Acid_i} * 0.03 + \frac{x_{z,Y'} * HHA_z}{\sum_{i=1}^{n} x_{i,Y'} * HHA_i} * 0.09 + \frac{x_{z,Y'} * Eut_z}{\sum_{i=1}^{n} x_{i,Y'} * Eut_i} * 0.06 + \frac{x_{z,Y'} * OD_z}{\sum_{i=1}^{n} x_{i,Y'} * OD_i} * 0.02 + \frac{x_{z,Y'} * Sm_z}{\sum_{i=1}^{n} x_{i,Y'} * Sm_i} * 0.04 + \frac{x_{z,Y'} * Eco_z}{\sum_{i=1}^{n} x_{i,Y'} * Eco_i} * 0.07 + \frac{x_{z,Y'} * HHC_z}{\sum_{i=1}^{n} x_{i,Y'} * HHC_i} * 0.08 + \frac{x_{z,Y'} * HHNC_z}{\sum_{i=1}^{n} x_{i,Y'} * HHNC_i} * 0.05 + \frac{x_{z,Y'} * PE_z}{\sum_{i=1}^{n} x_{i,Y'} * PE_i} * 0.10 + \frac{x_{z,Y'} * LU_z}{\sum_{i=1}^{n} x_{i,Y'} * LU_i} * 0.06 + \frac{x_{z,Y'} * WC_z}{\sum_{i=1}^{n} x_{i,Y'} * WC_i} * 0.08$$

Where

$Env_{z,Y'} =$ Environmental impact from industry z for final demand Y'

$GWP_z =$ Global warming potential per dollar of output for industry z

$Acid_z =$ Acidification per dollar of output for industry z

$HHA_z =$ Human health –criteria air pollutants – per dollar of output for industry z

$Eut_z =$ Eutrophication per dollar of output for industry z

$OD_z =$ Ozone depletion per dollar of output for industry z

$Sm_z =$ Smog per dollar of output for industry z

$Eco_z =$ Ecotoxicity per dollar of output for industry z

$HHC_z =$ Human health – carcinogens – per dollar of output for industry z

$HHNC_z =$ Human health – non-carcinogen – per dollar of output for industry z

$PE_z =$ Primary energy consumption per dollar of output for industry z

$LU_z =$ Land use per dollar of output for industry z

$WC_z =$ Water consumption per dollar of output for industry z

$x_{z,Y'} =$ Output for industry z with final demand Y'

i = industry i through n

2.2. Value Added

The total requirements matrix $W(I - BW)^{-1}$ from Equation 1, which shows the total output required to meet a given level of final demand, is multiplied by final demand in the input-output data to estimate the total output. The output required to produce a particular level of final demand can be calculated by altering final demand to Y'. For this analysis, Y' equals final demand for those NAICS codes representing the production and use of ground passenger transportation equipment and zero for those that do not.

Value added is calculated by assuming the proportion of output needed to produce a commodity is the same proportion of value added, which is consistent with methods proposed by Miller (2009). The proportions calculated using the input-output analysis are then multiplied by the value added and scaled to 2014 dollars using the estimate of gross output for that year:

Equation 3

$$VA_{z,Y',2014} = \frac{x_{z,Y',2007}}{x_{z,2007}} * VA_{z,2007} * \left(\frac{x_{z,2014}}{x_{z,2007}}\right)$$

Where

$VA_{z,Y',2014}$ = Value added from industry z with final demand Y' in 2014

$x_{z,2007}$ = Total output for industry z in 2007

$x_{z,2014}$ = Total output for industry z in 2014

$x_{z,Y',2007}$ = Output for industry z with final demand Y' in 2007

$VA_{z,2007}$ = Total value added from industry z in 2007

Imports are calculated in a similar fashion, where the proportion of total output used from a particular industry is the same for imports.

2.3. Production and Use

To examine both the production and use of a product, the Bureau of Economic Analysis' data on personal consumption expenditures by function is used, which includes categories for transportation. A list of resource consumption categories is provided in Figure 2. It includes items that are documented in the nation's gross domestic product and items that are not included. Some passenger transport is purchased by consumers while other purchases are made by other industries. Figure 2 separates these categories. Both categories have to purchase or pay for fuels along with maintenance and repair. Some of these items are imported while others are produced domestically. Consumers face costs, however, that are not documented in the economy, including the time spent in transport and time spent on maintenance and repair that they themselves conduct. There are also infrastructure costs that the public sector bears. Unfortunately, the environmental impact of personal fuel consumption is not captured in this assessment.

The US Census Bureau's American Time Use Survey is used to measure uncompensated labor such as driving time. Each purchase, including that for vehicles, public transport, vehicle maintenance and repair, and fuel, is entered into the input-output model. This calculation assumes that imported items face similar costs and impact as those produced domestically. Although this is not strictly accurate, imported products have similar materials and components. The value of uncompensated time is calculated by multiplying the average time use per year by the average hourly compensation for 2014, which is $32.05.

2.4. Sensitivity Analysis

This analysis uses data from previous years to guide research decisions for current industry activity, which results in some uncertainty. In order to account for this uncertainty, a probabilistic sensitivity analysis was conducted using Monte Carlo analysis. Examinations of uncertainty in environmental Input-

Output analysis have used both fuzzy set theory and stochastic models[17, 18, 19, 20, 21]; however, with there being limited in-depth examinations of uncertainty, there is not a consensus on a specific approach.[22] Monte Carlo analysis is based on works by McKay, Conover, and Beckman[23] and by Harris[24] that involves a method of model sampling. Monte Carlo simulation methods are superior to deterministic modeling for our purposes because deterministic modeling uses single-point estimates while Monte Carlo generates a probability distribution for every single variable of interest and allows for a comprehensive comparison of those probabilities.

The method was implemented using the Crystal Ball software product[25], a software add-in for spreadsheets. Specification involves defining which variables are to be simulated, the distribution of each of these variables, and the number of iterations performed. The software then randomly samples from the probabilities for each input variable of interest.

For this analysis, the industries that are above the 80th percentile for both environmental impact and value added were included in the Monte Carlo analysis, which includes 43 industries. For the environmental impact, each of the TRACI factors were varied by +/- 10 % and the weights are varied by +/- 25 %. For value added, each industry was varied by +/- 25 %. The remaining industries are varied together by +/- 10 %. Each variation uses a triangular distribution where the base case is the most likely value. Although different levels of variation could be selected, it has been shown that this level of error is consistent with previous works.[26, 27] This simulation contained 10 000 iterations.

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3. Data

Three datasets are needed to examine costs and environmental impacts. These datasets include the Bureau of Economic Analysis (BEA) Benchmark Input-Output data, Personal Consumption Expenditures from the BEA, environmentally extended input-output data, and the American Time Use Survey.

Input-Output Data and Personal Consumption Expenditures: Every five years the BEA computes benchmark input-output tables, which tends to have over 350 industries.[28] The data is provided in the form of make and use tables, with their corresponding matrices replacing the Leontief method.[29] In the US, industries are categorized by NAICS codes. There are two types of make and use tables: "standard" and "supplementary." Standard tables closely follow NAICS and are consistent with other economic accounts and industry statistics, which classify data based on establishment. Note that in this context an "establishment" is a single physical location where business is conducted. This should not be confused with an "enterprise" such as a company, corporation, or institution. Establishments are classified into industries based on the primary activity within the NAICS code definitions; however, establishments often have multiple activities. An establishment is classified based on its primary activity. Data for an industry reflects all the products made by the establishments within that industry; therefore, secondary products are included. Supplementary make-use tables reassign secondary products to the industry in which they are primary products. The data in this report utilizes the standard make-use tables. The BEA uses the data for the input-output accounts to also estimate personal consumption expenditures.*Environmental Data*: For environmental data, this paper applies a suite of environmentally extended Input-Output databases for Life Cycle Assessments (LCA) developed under contract for NIST by Dr. Sangwon Suh of the Bren School of Environmental Science and Management at the University of California, Santa Barbara.[30] This data has been utilized in a number of environmental efforts, including NIST's Building for Environmental and Economic Sustainability (BEES)[31] and Building Industry Reporting and Design for Sustainability (BIRDS)[32] software and related publications. This data utilizes the 12 TRACI 2 impact categories: global warming potential, primary energy consumption, human health – criteria air pollutants, human health – carcinogens, water consumption, ecological toxicity[33], eutrophication[34], land use, human health – non-carcinogens, smog formation, acidification, and ozone depletion. The units of measurement are provided in Table 1. This environmental data is organized by 2002 BEA codes for the Benchmark Input-Output tables, and matched and adjusted to the 2007 BEA Input-Output tables. The environmental data was adjusted from being in impact units per 2002 dollars to impact units per 2007 dollars using the consumer price index from the Bureau of Labor Statistics.

American Time Use Survey: The American Time Use Survey estimates how and where the US population spends its time, including time spent at work, leisure activities, childcare, transportation, and household activities. The data is collected from a sample size of approximately 40 500 and conducted annually.

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[31] National Institute of Standards and Technology. Building for Environmental and Economic Sustainability. Accessed September 2016. http://www.nist.gov/el/economics/BEESSoftware.cfm.

[32] National Institute of Standards and Technology. Building Industry Reporting and Design for Sustainability. Accessed September 2016. https://birdscom.nist.gov/.

[33] The potential of a chemical released into the environment to harm terrestrial and aquatic ecosystems.

[34] The addition of mineral nutrients to the soil or water, which in large quantities can result in generally undesirable shifts in the number of species in ecosystems and a reduction in ecological diversity

4. Results and Discussion

Public entities, trade organizations, and other change agents that seek to maximize efficiency improvement through innovative solutions must prioritize their efforts to get the largest reduction per expenditure dollar. In a world of limited and scarce resources, it is not technically feasible to identify all possible research topics, conduct an economic analysis of each, and identify those with the highest return. Rather, researchers can only identify a selection of the possible R&D topics. Those topics that are within high cost areas of production and use have a higher likelihood of having a large impact and return-on-investment. After identifying high cost/impact areas, potential research topics within those cost areas can be identified and compared.

Table 2 presents the costs associated with ground passenger transport along with an estimate of the uncompensated time spent in transport, referred to as resources. The total is approximately $4.9 trillion, which is 14.9 % of the total resources in the US (the total includes an estimate for uncompensated time spent working). The largest cost item is the consumer transport time, which amounts to $3.3 trillion or 68 % of the total resource cost. A great deal of travel time is spent going to and from the store to purchase goods/services, as seen in Table 3. The next largest is transportation to and from work with leisure/other being third. The second largest cost in Table 2 is the fuels, maintenance, and repair. The consumer, commercial, and industrial purchases amount to $1.1 trillion. The implication of these results is that the product design, infrastructure, and reducing the need for transportation can have a disproportional impact, compared to other cost items, on the resource consumption for ground passenger transit. For instance, reducing the need for transportation by allowing employees to telecommute and improving telecommunications might have a larger reduction in resource consumption than other targeted efforts, as it reduces the largest cost item – transport time; however, only a limited number of jobs can facilitate telecommuting. Other potential resource saving efforts might include alleviating traffic congestion or facilitating the delivery of goods. Increasing fuel efficiency and reducing maintenance/repair needs can also have a disproportional impact. The advancement of autonomous (i.e., self-driving) vehicles can also improve efficiency, as it could, potentially, allow the operator to conduct other activities.

The items included as expenditures (i.e., everything except uncompensated time) were examined using input-output analysis to identify other top cost items. Forty-three industries were identified as being above the 80th percentile for both value added and environmental impact, as illustrated in Figure 3 and listed in Table 4. This figure and table includes the resources used for both production and use of transportation equipment. Six industries are listed as having both the environmental impact and value added as being above the 95th percentile: “211000 oil and gas extraction”; “iron and steel mills and ferroalloy manufacturing”; “336111 automobile manufacturing”; “324111 automobile manufacturing”; “324110 petroleum refineries”; “485000 transit and ground passenger transportation”; and “811100 automotive repair and maintenance.” It is important to note that industries associated with fuel production (e.g., “211000 oil and gas extraction” and “324110 petroleum refineries”) are associated with even greater environmental impact, as this analysis was unable to capture the burning of fuel in personal vehicles. Efficiency improvements in these areas can have a disproportional impact on resource consumption when compared to other supply chain industries (i.e., cost items). For instance, a 1 % reduction in “211000 oil and gas extraction” amounts to a total 0.35 % reduction in the total cost, a larger reduction than any other industry. It also would result in a 0.16 % decrease in the environmental impact, which is the second largest of any supply chain industry. Increasing fuel efficiency through light weighting can reduce costs and environmental impacts from “211000 oil and gas extraction” and “324110 petroleum refineries” while also reducing material costs. Increased efficiency in automobile assembly can reduce “336111 automobile manufacturing.” Currently, it is difficult for consumers to compare the maintenance costs of various vehicles; therefore, standards for measuring and comparing maintenance and repair costs for automobiles might facilitate reducing costs from “811100 automotive repair and maintenance.”

The value added items and the environmental impacts shown in Figure 3 correlate with a coefficient of 0.78, suggesting that production costs and environmental impacts can be reduced simultaneously. The results from the Monte Carlo analysis, also shown in Table 4, do not have any industry above the 80th percentile that varies more than 5.2 percentile points. Only four of the industries drop below the 80th percentile. Moreover, these results suggest that the rankings of cost and environmental impact are fairly robust.

5. Conclusion

National governments invest in research and development efforts that advance efficiency and spur economic growth. There are, however, few studies that identify the efforts that will have the largest possible return on investment, resulting in the funding of investments with suboptimal returns. Previous work has focused on examining production costs; however, to identify high-return areas of research all costs, both the production and use of a product, need to be considered. This paper examines the life-cycle cost of passenger ground transportation as a proof of concept to identify areas of public research that might have a high return on investment. It uses input-output analysis to examine the supply chain for production and use of transportation equipment. Future research might expand the analysis to examine multiple product categories rather than focusing on transportation alone.

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Figure 1: Implicit Goals of Public Research in Manufacturing

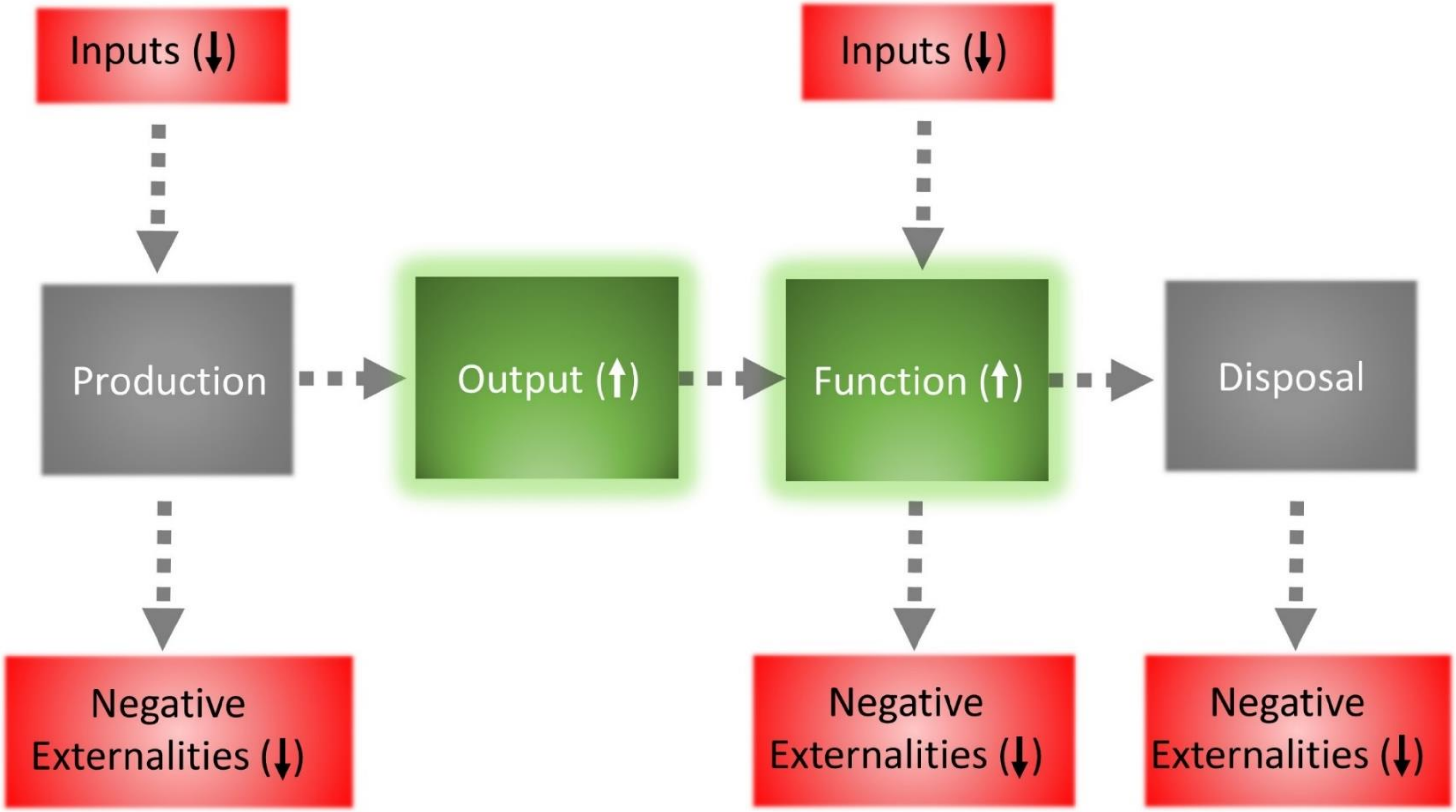

Figure 2: Domestic Resource Consumption Map for Discrete Manufactured Goods

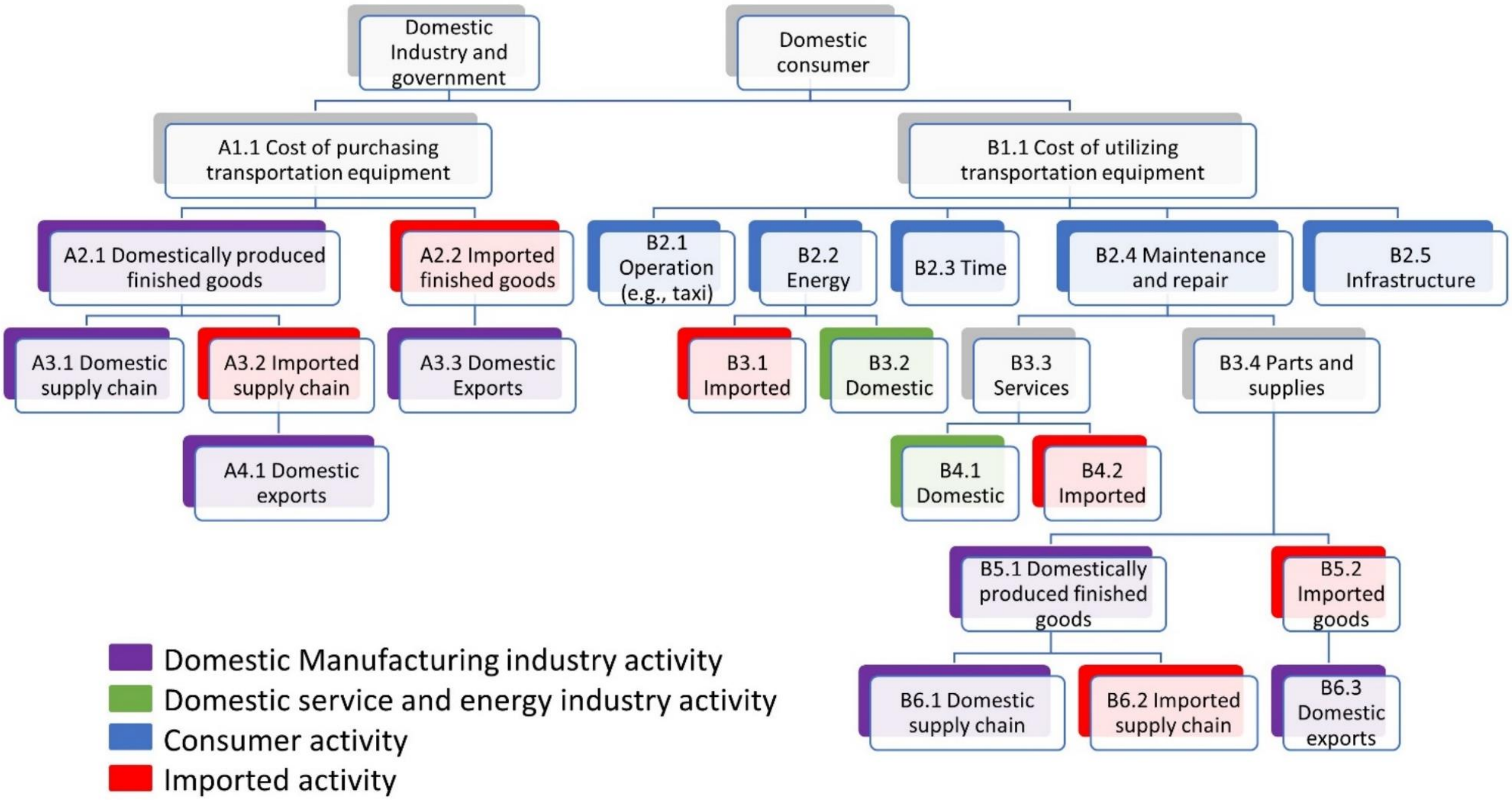

Table 1: Environmental Impact Categories and Weights for Assessing Impact

Items to be measured	**Units**	**Weights**
Global Warming Potential	kg CO_2 eq	0.30
Acidification	H^+ moles eq	0.03
Human Health- Criteria Air Pollutants	kg PM_{10} eq	0.09
Eutrophication	kg N eq	0.06
Ozone Depletion	kg CFC-11 eq	0.02
Smog	kg O_3 eq	0.04
Ecotoxicity	CTUe	0.07
Human Health - Carcinogens	CTUHcan	0.08
Human Health – Non- Carcinogens	CTUHnoncan	0.05
Primary Energy Consumption	thousand BTU	0.10
Land Use	acre	0.06
Water Consumption	kg	0.08

Table 2: Resources Related to Ground Passenger Transport, 2014

	$Billion 2014	Percent of Total Resources
Consumer purchases (A1.1)	**266.1**	**0.8%**
New motor vehicles	266.1	0.8%
Consumer maintenance, repair, and energy (B2.1, B2.2, B2.4)	**931.8**	**2.8%**
Public Transportation	99.8	0.3%
Motor vehicle parts and accessories	65.4	0.2%
Motor vehicle fuels, lubricants, and fluids	371.2	1.1%
Motor vehicle maintenance and repair	176.7	0.5%
Other motor vehicle services	77.6	0.2%
Consumer time usage for maintenance and repair (dollar equivalent)	141.1	0.4%
Vehicle maintenance and repair not done by self	28.2	0.1%
Vehicles	112.9	0.3%
Consumer transport time (B2.3)	**3329.6**	**10.2%**
Consumer time usage (dollar equivalent)	3329.6	10.2%
Travel (for work)	761.9	2.3%
Travel (other)	2567.8	7.8%
Commercial, industrial, and other maintenance, repair, and energy (B1.1)	**170.3**	**0.5%**
Gasoline**	170.3	0.5%
Commercial, industrial, and other purchases (B1.1)	**122.1**	**0.4%**
New motor vehicles	122.1	0.4%
Infrastructure	**76.9**	**0.2%**
Highways and streets	76.9	0.2%
Total - Resources related to discrete manufactured products	4896.8	14.9%
Total - annual resources (GDP and uncompensated labor time)	32771.5	100.0%

* Adjusted to 2014 using the Consumer Price Index for all consumers

** Assumes the ratio of new motor vehicle purchases to Motor vehicle fuels, lubricants, and fluids is the same for consumers as it is for commercial and industrial uses

Source: Bureau of Economic Analysis. (2016) Personal Consumption Expenditures by Function. Table 2.5.5. https://www.bea.gov/itable/index.cfm.

Source: Energy Information Administration. 2009 Residential Energy Consumption Survey. Table CE4.11. https://www.eia.gov/consumption/residential/data/2009/index.php?view=consumption.

Source: Bureau of Labor Statistics. (2016) American Time Use Survey. Table A-1. https://www.bls.gov/tus/a1_2016.pdf.

Table 3: Time Spent Utilizing/Maintaining Transportation Equipment, 2016

Category of time use	Hours per year	Percent of hours awake	Annual time value* ($Billion)
Travel (personal care)	10.95	0.2%	84.65
Travel (eating and drinking)	40.15	0.7%	310.39
Travel (household activities)	18.25	0.3%	141.09
Travel (purchasing goods/services)	105.85	1.9%	818.30
Travel (care of others)	51.10	0.9%	395.04
Travel (for work)	98.55	1.8%	761.87
Travel (for education)	10.95	0.2%	84.65
Travel (for leisure and other)	94.90	1.7%	733.65
Vehicle maintenance and repair not done by self	3.65	0.1%	28.22
Vehicles	14.60	0.3%	112.87
TOTAL	448.95	8.1%	3470.72

* Applying the average hourly compensation for 2014 ($32.305/hour)
Source: Bureau of Labor Statistics. (2016) American Time Use Survey. Table A-1. https://www.bls.gov/tus/a1_2016.pdf.

Figure 3: Environmental Impact and Value Added for the Annualized Life-Cycle Cost of US Passenger Transportation, Percentile

Table 4: Environmental Impact and Value Added for the Annualized Life-Cycle Cost of US Passenger Transportation, Percentile

		Environmental				Value Added			
		Base Case	Mean	Minimum	Maximum	Base Case	Mean	Minimum	Maximum
211000 Oil and gas extraction	**	99.5	99.5	99.5	99.5	99.8	99.8	99.8	99.8
212100 Coal mining		92.9	92.7	91.1	94.1	85.0	84.9	81.0	87.7
2122A0 Iron, gold, silver, and other metal ore mining		96.8	96.8	96.1	97.5	81.0	81.2	76.1	85.2
21311A Other support activities for mining	*	94.1	94.2	93.8	94.6	92.4	92.3	88.4	94.3
221100 Electric power generation, transmission, and distribution		97.8	97.9	97.5	98.3	87.2	87.1	84.2	90.1
230301 Nonresidential maintenance and repair	*	92.6	92.7	91.6	93.6	96.3	95.9	94.3	96.3
233293 Highways and streets		86.9	86.8	85.5	87.9	97.3	97.3	96.8	97.8
327200 Glass and glass product manufacturing	*	98.0	97.9	97.5	98.0	90.4	90.1	86.7	92.9
331110 Iron and steel mills and ferroalloy manufacturing	**	98.8	98.7	98.5	98.8	96.8	96.8	96.6	97.3
331200 Steel product manufacturing from purchased steel		90.9	90.9	89.2	92.1	86.0	85.8	82.3	88.4
33131A Alumina refining and primary aluminum production		91.9	91.8	90.9	93.3	85.2	85.2	81.0	87.9
331411 Primary smelting and refining of copper		85.5	85.5	84.0	86.7	85.7	85.8	81.8	88.4
331419 Primary smelting and refining of nonferrous metal (except copper and aluminum)		86.0	85.9	84.5	86.9	93.8	93.9	91.1	95.3
331490 Nonferrous metal (except copper and aluminum) rolling, drawing, extruding and alloying		89.4	89.2	88.4	90.1	82.8	82.6	77.6	85.7
331510 Ferrous metal foundries		91.1	91.3	90.6	92.1	88.2	88.3	85.0	91.6
331520 Nonferrous metal foundries		93.8	93.8	93.1	94.3	88.4	88.6	85.2	91.9
332310 Plate work and fabricated structural product manufacturing		87.4	87.4	86.2	87.9	86.7	86.7	84.0	89.9
332710 Machine shops		81.8	81.7	80.0	83.5	89.2	89.4	86.0	92.6
332720 Turned product and screw, nut, and bolt manufacturing		86.7	86.6	85.5	87.4	93.3	93.0	89.9	94.8
332800 Coating, engraving, heat treating and allied activities		85.2	85.1	83.7	86.5	82.0	82.0	77.1	85.5
33299B Other fabricated metal manufacturing		84.2	84.3	83.0	85.2	82.3	82.1	77.1	85.5
333618 Other engine equipment manufacturing	*	90.1	90.1	89.4	91.1	95.8	95.7	93.8	96.3
33441A Other electronic component manufacturing		91.6	91.7	90.9	92.6	89.9	89.7	86.2	92.6
336111 Automobile manufacturing	**	99.3	99.3	99.3	99.3	99.3	99.1	98.3	99.3
336310 Motor vehicle gasoline engine and engine parts manufacturing		89.7	89.8	88.9	90.6	99.0	99.0	98.3	99.3
336350 Motor vehicle transmission and power train parts manufacturing		83.0	82.9	81.3	84.5	97.0	97.1	96.8	97.5
336390 Other motor vehicle parts manufacturing		87.2	87.4	86.5	87.9	97.5	97.5	97.0	98.0
316000 Leather and allied product manufacturing	*	96.1	96.1	95.8	97.0	90.9	90.6	86.9	93.3
324110 Petroleum refineries	**	99.8	99.8	99.8	99.8	99.5	99.5	99.5	99.5
325110 Petrochemical manufacturing	*	96.6	96.5	96.1	97.0	91.4	91.0	87.4	93.6
325190 Other basic organic chemical manufacturing		97.3	97.3	96.8	97.5	87.7	87.7	84.7	90.6
325211 Plastics material and resin manufacturing		94.8	95.0	94.8	95.6	85.5	85.6	81.8	88.2
326190 Other plastics product manufacturing	*	92.4	92.7	91.6	93.6	92.6	92.5	88.9	94.8
326210 Tire manufacturing		87.7	87.6	86.7	88.2	84.7	84.7	80.5	87.4
420000 Wholesale trade	*	94.6	94.5	94.1	94.8	98.5	98.6	98.0	99.3
482000 Rail transportation		93.1	92.8	91.4	93.8	87.9	88.0	85.0	91.1
484000 Truck transportation	*	95.8	95.8	95.6	96.1	94.8	94.7	92.6	96.3
485000 Transit and ground passenger transportation	**	98.3	98.3	98.0	98.3	98.0	98.0	97.5	98.3
486000 Pipeline transportation	*	96.3	96.3	96.1	97.0	93.1	92.8	89.4	94.8
550000 Management of companies and enterprises		89.9	90.0	88.9	90.9	97.8	97.8	97.3	98.0
561700 Services to buildings and dwellings		84.7	84.3	80.5	86.5	89.7	89.6	86.2	93.1
562000 Waste management and remediation services		95.3	95.4	95.1	95.6	84.2	84.0	79.8	86.7
811100 Automotive repair and maintenance	**	99.0	99.0	99.0	99.0	98.8	98.7	98.3	99.3

** Both environmental impact and value added are above the 95th percentile

* Both environmental impact and value added are above the 90th percentile, but below the 95th