# Quantifying material and carbon reduction in circular consumption: solving selected methodological and data challenges while accounting for rebound effects

Amatuni, L.T.

# References

Afrinaldi, F. (2020). Exploring product lifecycle using Markov chain. *Procedia Manufacturing*, *43*, 391–398. https://doi.org/10.1016/j.promfg.2020.02.196

Aguilar-Hernandez, G. A., Dias Rodrigues, J. F., & Tukker, A. (2021). Macroeconomic, social and environmental impacts of a circular economy up to 2050: A meta-analysis of prospective studies. *Journal of Cleaner Production*, *278*, 123421. https://doi.org/10.1016/j.jclepro.2020.123421

Aguilar-Hernandez, G. A., Sigüenza-Sanchez, C. P., Donati, F., Rodrigues, J. F. D., & Tukker, A. (2018). Assessing circularity interventions: a review of EEIOA-based studies. *Journal of Economic Structures*, *7*(1). https://doi.org/10.1186/s40008-018-0113-3

Amatuni, L. (2023). *Product Lifetimes & Durability Portal*. https://lt-platform.web.app/

Amatuni, L., Ottelin, J., Steubing, B., & Mogollón, J. M. (2020). Does car sharing reduce greenhouse gas emissions? Assessing the modal shift and lifetime shift rebound effects from a life cycle perspective. *Journal of Cleaner Production*, *266*, 121869. https://doi.org/10.1016/j.jclepro.2020.121869

Amatuni, L., Yamamoto, T., Baldé, C. P., Clemm, C., & Mogollón, J. M. (2023). Quantifying total lifetimes of consumer products: Stochastic modelling accounting for second-hand use and establishing an open-collaborative database. *Resources, Conservation and Recycling*, *197*, 107103. https://doi.org/10.1016/J.RESCONREC.2023.107103

André, H., Ljunggren Söderman, M., & Nordelöf, A. (2019). Resource and environmental impacts of using second-hand laptop computers: A case study of commercial reuse. *Waste Management*, *88*, 268–279. https://doi.org/10.1016/j.wasman.2019.03.050

ASA, A. S. (2020). *Adevinta Sustainability Report 2020. Creating perfect matches on the world's most trusted marketplaces*.

Babbitt, C. W., Madaka, H., Althaf, S., Kasulaitis, B., & Ryen, E. G. (2020). Disassembly-based bill of materials data for consumer electronic products. *Scientific Data*, *7*(1), 251. https://doi.org/10.1038/s41597-020-0573-9

Baldé, C. P., Iattoni, G., Xu, C., & Yamamoto, T. (2021). *Update of WEEE Collection Rates, Targets, Flows, and Hoarding-2021*.

Barnett, M. J., Hancock, P. I., Klotz, L. E., & Attari, S. Z. (2023). Recycling bias and reduction neglect. *Nature Sustainability*, 1–8. https://doi.org/10.1038/s41893-023-01185-7

Behan, K., & Lea, N. S. (2014). Benchmarking Active Transportation In Canadian Cities. In *Clean Air Partnership*.

Beylot, A., Ardente, F., Sala, S., & Zampori, L. (2020). Accounting for the dissipation of abiotic resources in LCA: Status, key challenges and potential way forward. *Resources, Conservation and Recycling*, *157*(February), 104748. https://doi.org/10.1016/j.resconrec.2020.104748

Blondel, B., Mispelon, C., & Ferguson, J. (2011). Cycle More Often 2 Cool Down The Planet! - Quantifying CO2 savings of Cycling. In *European Cyclists' Federation*.

Borenstein, S. (2014). A Microeconomic Framework for Evaluating Energy Efficiency Rebound and Some Implications. *The Energy Journal*, *36*(1), 1–21. https://doi.org/10.5547/01956574.36.1.1

Braungart, M., & McDonough, W. (2013). The Upcycle: Beyond Sustainability – Designing for Abundance. *International Journal of Sustainability in Higher Education*, *14*(4), 4–12. https://doi.org/10.1108/ijshe.2013.24914daa.010

*Car2Go: Pioneer And Market Leader In Free-Floating Carsharing*. (2017). Car2Go. https://www.car2go.com/media/data/germany/microsite-press/files/factsheet-car2go_november-2017_en.pdf

*Car2Go: Press Release*. (2018). Car2Go. https://www.car2go.com/media/data/germany/microsite-press/files/20180731_press-release_car2go-launches-in-chicago-and-grows-worldwide.pdf

Castro, C. G., Trevisan, A. H., Pigosso, D. C. A., & Mascarenhas, J. (2022). The rebound effect of circular economy: Definitions, mechanisms and a research agenda. *Journal of Cleaner Production*, *345*, 131136. https://doi.org/10.1016/j.jclepro.2022.131136

Cervero, R., Golub, A., & Nee, B. (2007). City CarShare: Longer-Term Travel Demand and Car Ownership Impacts. *Transportation Research Record: Journal of the Transportation Research Board*, *1992*(1), 70–80. https://doi.org/10.3141/1992-09

Cervero, R., & Tsai, Y. (2004). City CarShare in San Francisco, California: Second-Year Travel Demand and Car Ownership Impacts. *Transportation Research Record: Journal of the Transportation Research Board*, *1887*(1), 117–127. https://doi.org/10.3141/1887-14

Chen, C.-W. (2021). Clarifying rebound effects of the circular economy in the context of sustainable cities. *Sustainable Cities and Society*, *66*, 102622. https://doi.org/10.1016/j.scs.2020.102622

Chen, H., & Zhang, F. (2008). The expected hitting times for finite Markov chains. *Linear Algebra and Its Applications*, *428*(11–12). https://doi.org/10.1016/j.laa.2008.01.003

Chen, T. D., & Kockelman, K. M. (2016). Carsharing's life-cycle impacts on energy use and greenhouse gas emissions. *Transportation Research Part D: Transport and Environment*, *47*, 276–284. https://doi.org/10.1016/j.trd.2016.05.012

Chester, M. (2008). Life-cycle environmental inventory of passenger transportation in the United States. In *Institute of Transportation Studies*. UC Berkeley.

Chester, M. V., & Horvath, A. (2009). Environmental assessment of passenger transportation should include infrastructure and supply chains. *Environmental Research Letters*, *4*(2). https://doi.org/10.1088/1748-9326/4/2/024008

Ching, A. T., Erdem, T., & Keane, M. P. (2020). How much do consumers know about the quality of products? Evidence from the diaper market. *Japanese Economic Review*, *71*(4), 541–569. https://doi.org/10.1007/s42973-019-00030-x

Chmielewski, M., & Kucker, S. C. (2020). An MTurk Crisis? Shifts in Data Quality and the Impact on Study Results. *Social Psychological and Personality Science*, *11*(4), 464–473. https://doi.org/10.1177/1948550619875149

Cooper, D., & Gutowski, T. (2017). The Environmental Impacts of Reuse: A Review. *Journal of Industrial Ecology*, *21*(1), 38–56. https://doi.org/10.1111/jiec.12388

Cooper, T. (2005). Slower consumption: Reflections on product life spans and the "throwaway society." *Journal of Industrial Ecology*, *9*(1–2), 51–67. https://doi.org/10.1162/1088198054084671

Cooper, T. (2020). Slower cycles: An essential characteristic of the circular economy. In *The Circular Economy in the European Union: An Interim Review* (pp. 99–116). Springer International Publishing. https://doi.org/10.1007/978-3-030-50239-3_9

Cordella, M., Alfieri, F., & Sanfelix, J. (2021). Reducing the carbon footprint of ICT products through material efficiency strategies: A life cycle analysis of smartphones. *Journal of Industrial Ecology*, *25*(2), 448–464. https://doi.org/10.1111/jiec.13119

Corvellec, H., Stowell, A. F., & Johansson, N. (2022). Critiques of the circular economy. *Journal of Industrial Ecology*, *26*(2), 421–432. https://doi.org/10.1111/jiec.13187

Csutora, M. (2012). The ecological footprint of green and brown consumers. Introducing the behaviour-impact-gap ( BIG ) problem. *15th European Roundtable on Sustainable Consumption and Production*.

Daglis, T. (2022). Sharing Economy. *Encyclopedia 2022, Vol. 2, Pages 1322-1332*, *2*(3), 1322–1332. https://doi.org/10.3390/ENCYCLOPEDIA2030088

Dalhammar, C., Milios, L., & Luth Richter, J. (2021). *Increasing the lifespan of products. Policies and consumer perspectives*.

Daniotti, B., Lupica Spagnolo, S. Chevalier, J. L., Hans, J., & Chorier, J. (2010). An International Service Life Database: The Grid Definition for an Actual Implementation of Factor Methods and Service Life Prediction. *CIB 2010 World Congress*. https://doi.org/http://dx.doi.org/10.13140/RG.2.1.2457.1369/1

Ding, N., Pan, J., Zhang, Z., & Yang, J. (2019). Life cycle assessment of car sharing models and the effect on GWP of urban transportation: A case study of Beijing. *Science of the Total Environment*, *688*, 1137–1144. https://doi.org/10.1016/j.scitotenv.2019.06.111

Dionisio, K. L., Phillips, K., Price, P. S., Grulke, C. M., Williams, A., Biryol, D., Hong, T., & Isaacs, K. K. (2018). Data Descriptor: The Chemical and Products Database, a resource for exposure-relevant data on chemicals in consumer products. *Scientific Data*. https://doi.org/10.1038/sdata.2018.125

Donati, F., Aguilar-Hernandez, G. A., Sigüenza-Sánchez, C. P., de Koning, A., Rodrigues, J. F., & Tukker, A. (2020). Modeling the circular economy in environmentally extended input-output tables: Methods, software and case study. *Resources, Conservation and Recycling*, *152*, 104508. https://doi.org/10.1016/j.resconrec.2019.104508

Dun, C., Horton, G., & Kollamthodi, S. (2015). Improvements to the definition of lifetime mileage of light duty vehicles. In *Report for European Commission – DG Climate Action* (Issue 1).

Dunant, C. F., Shah, T., Drewniok, M. P., Craglia, M., & Cullen, J. M. (2021). A new method to estimate the lifetime of long-life product categories. *Journal of Industrial Ecology*, *25*(2), 321–332. https://doi.org/10.1111/JIEC.13093

EIA. (2016). International Energy Outlook 2016: U.S. Energy Information Administration (EIA), Washington DC. In *Office of Integrated and International Energy Analysis* (Vol. 1, Issue May).

Eisenstein, M. (2022). Short-circuiting the electronic-waste crisis. *Nature*, *611*(7936), S8–S10. https://doi.org/10.1038/d41586-022-03647-y

Ellen MacArthur Foundation. (2023). *What is a circular economy?* https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview

Energie Beheer Nederland. (2018). *Energy in the Netherlands*.

European Commission. (2001). *Environmental pressure indicators for the EU*.

European Commission - Joint Research Centre - Institute for Environment and Sustainability. (2010). International Reference Life Cycle Data System ( ILCD ) Handbook : Specific guide for Life Cycle Inventory data sets. EUR 24709 EN. In *European Commission*. https://doi.org/10.2788/39726

European Parliament. (2023). *Circular economy: definition, importance and benefits | News | European Parliament*. News, Headlines, Economy. https://www.europarl.europa.eu/news/en/headlines/economy/20151201STO05603/circular-economy-definition-importance-and-benefits

Feldman, R. M., & Valdez-Flores, C. (2010). Applied probability and stochastic processes. In *Applied Probability and Stochastic Processes*. https://doi.org/10.1007/978-3-642-05158-6

Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., & Suh, S. (2009). Recent developments in Life Cycle Assessment. In *Journal of Environmental Management*. https://doi.org/10.1016/j.jenvman.2009.06.018

Floyd, K., Freling, R., Alhoqail, S., Cho, H. Y., & Freling, T. (2014). How online product reviews affect retail sales: A meta-analysis. *Journal of Retailing*, *90*(2), 217–232. https://doi.org/10.1016/j.jretai.2014.04.004

Font Vivanco, D., Freire-González, J., Kemp, R., & Van Der Voet, E. (2014). The remarkable environmental rebound effect of electric cars: A microeconomic approach. *Environmental Science and Technology*, *48*(20), 12063–12072. https://doi.org/10.1021/es5038063

Forti, V., Baldé, C. P., & Kuehr, R. (2018). E-waste Statistics: Guidelines on Classifications, Reporting and Indicators, second edition. In *United Nations University, IAS-SCYCLE* (Issue February).

Frenken, K., Meelen, T., Arets, M., & van de Glind, P. B. (2015). *Smarter regulation for the sharing economy*. The Guardian. http://www.theguardian.com/science/political-science/2015/may/20/smarter-regulation-for-the-sharing-economy

Frenken, K., & Schor, J. (2017). Putting the sharing economy into perspective. *Environmental Innovation and Societal Transitions*, *23*, 3–10. https://doi.org/10.1016/j.eist.2017.01.003

Frenken, K., Waes, A. van, Smink, M., & Est, R. van. (2017). A fair share – Safeguarding public interests in the sharing and gig economy. In *The Rathenau Instituut*.

Frosch, R. A., & Gallopoulos, N. E. (1989). Strategies for Manufacturing. *Scientific American*, *261*(3), 144–152. https://doi.org/10.1038/scientificamerican0989-144

Frost & Sullivan. (2010). *Analysis of the Market for Carsharing in North America*.

Göddeke, D., Krauss, K., & Gnann, T. (2022). What is the role of carsharing toward a more sustainable transport behavior? Analysis of data from 80 major German cities. *International Journal of Sustainable Transportation*, *16*(9). https://doi.org/10.1080/15568318.2021.1949078

Greening, A. L., Greene, D. L., & Difiglio, C. (2000). Energy efficiency and consumption — the rebound effect — a survey. *Energy Policy*, *28*(6–7), 389–401. https://doi.org/10.1016/S0301-4215(00)00021-5

Grischkat, S., Hunecke, M., Böhler, S., & Haustein, S. (2014). Potential for the reduction of greenhouse gas emissions through the use of mobility services. *Transport Policy*. https://doi.org/10.1016/j.tranpol.2014.06.007

Hájek, M., Zimmermannová, J., Helman, K., & Rozenský, L. (2019). Analysis of carbon tax efficiency in energy industries of selected EU countries. *Energy Policy*, *134*. https://doi.org/10.1016/j.enpol.2019.110955

Hart, J., & Pomponi, F. (2021). A Circular Economy: Where Will It Take Us? *Circular Economy and Sustainability*, *1*(1), 127–141. https://doi.org/10.1007/s43615-021-00013-4

Hartl, B., Sabitzer, T., Hofmann, E., & Penz, E. (2018). "Sustainability is a nice bonus" the role of sustainability in carsharing from a consumer perspective. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2018.08.138

Heeren, N., & Fishman, T. (2019). A Database Seed for a Community-driven Material Intensity Research Platform. *Scientific Data*, 1–10. https://doi.org/10.1038/s41597-019-0021-x

Heijungs, R., & Suh, S. (2002). The Computational Structure of Life Cycle Assessment. In *Springer Science & Business Media* (Vol. 11). Springer Netherlands. https://doi.org/10.1007/978-94-015-9900-9

Hennies, L., & Stamminger, R. (2016). An empirical survey on the obsolescence of appliances in German households. *Resources, Conservation and Recycling*, *112*, 73–82. https://doi.org/10.1016/j.resconrec.2016.04.013

Henry, M., Schraven, D., Bocken, N., Frenken, K., Hekkert, M., & Kirchherr, J. (2021). The battle of the buzzwords: A comparative review of the circular economy and the sharing economy concepts. *Environmental Innovation and Societal Transitions*, *38*, 1–21. https://doi.org/10.1016/j.eist.2020.10.008

Hertwich, E. G. (2005). Life cycle approaches to sustainable consumption: A critical review. *Environmental Science and Technology*, *39*(13), 4673–4684. https://doi.org/10.1021/es0497375

Hertwich, E. G. (2011). The Life Cycle Environmental Impacts Of Consumption. In *Economic Systems Research* (Vol. 23, Issue 1, pp. 27–47). https://doi.org/10.1080/09535314.2010.536905

Hertwich, E., Lifset, R., Pauliuk, S., Heeren, N., Ali, S., Tu, Q., Ardente, F., Berrill, P., Fishman, T., Kanaoka, K., Makov, T., Masanet, E., Wolfram, P., Acheampong, E., Beardsley, E., Calva, T., Ciacci, L., Clifford, M., Eckelman, M., … Zhu, B. (2020). Resource Efficiency and Climate Change: Material Efficiency Strategies for a Low-Carbon Future. In *International Resource Panel (IRP)*. https://doi.org/10.5281/zenodo.3542680

Hoekstra, R. (2019). Replacing GDP by 2030. In *Replacing GDP by 2030: Towards a Common Language for the Well-being and Sustainability Community*. Cambridge University Press. https://doi.org/10.1017/9781108608558

Hoekstra, R., & van den Bergh, J. C. J. M. (2006). Constructing physical input-output tables for environmental modeling and accounting: Framework and illustrations. *Ecological Economics*, *59*(3), 375–393. https://doi.org/10.1016/j.ecolecon.2005.11.005

Hollingsworth, J., Copeland, B., & Johnson, J. X. (2019). Are e-scooters polluters? the environmental impacts of shared dockless electric scooters. *Environmental Research Letters*. https://doi.org/10.1088/1748-9326/ab2da8

Horta Arduin, R., Mathieux, F., Huisman, J., Blengini, G. A., Charbuillet, C., Wagner, M., Baldé, C. P., & Perry, N. (2020). Novel indicators to better monitor the collection and recovery of (critical) raw materials in WEEE: Focus on screens. *Resources, Conservation and Recycling*, *157*(March), 104772. https://doi.org/10.1016/j.resconrec.2020.104772

Iacovidou, E., Hahladakis, J. N., & Purnell, P. (2021). A systems thinking approach to understanding the challenges of achieving the circular economy. *Environmental Science and Pollution Research*, *28*(19), 24785–24806. https://doi.org/10.1007/s11356-020-11725-9

IRS. (2023). *Gig Economy Tax Center | Internal Revenue Service*. https://www.irs.gov/businesses/gig-economy-tax-center

ISO. (2006). 14040: Environmental management–life cycle assessment—Principles and framework. *International Organization for Standardization*.

Jackson, T. (2009). Prosperity Without Growth? The transition to a sustainable economy. In *Growth in Transition*. Sustainable Development Commission. https://doi.org/10.4324/9780203145593-12

Jaeger-Erben, M., Frick, V., & Hipp, T. (2021). Why do users (not) repair their devices? A study of the predictors of repair practices. *Journal of Cleaner Production*, *286*, 125382. https://doi.org/10.1016/J.JCLEPRO.2020.125382

Jensen, J. P., & Remmen, A. (2017). Enabling Circular Economy Through Product Stewardship. *Procedia Manufacturing*. https://doi.org/10.1016/j.promfg.2017.02.048

Jevons, W. S. (2018). The Coal Question. In *The Economics of Population: Key Classic Writings*. https://doi.org/10.4324/9781351291521-27

Jones, C., Gilbert, P., Raugei, M., Mander, S., & Leccisi, E. (2017). An approach to prospective consequential life cycle assessment and net energy analysis of distributed electricity generation. *Energy Policy*, *100*, 350–358. https://doi.org/https://doi.org/10.1016/j.enpol.2016.08.030

Jung, J., & Koo, Y. (2018). Analyzing the effects of car sharing services on the reduction of greenhouse gas (GHG) emissions. *Sustainability (Switzerland)*, *10*(2), 1–17. https://doi.org/10.3390/su10020539

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, *127*, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Klinglmair, M., Sala, S., & Brandão, M. (2014). Assessing resource depletion in LCA: A review of methods and methodological issues. *International Journal of Life Cycle Assessment*, *19*(3), 580–592. https://doi.org/10.1007/s11367-013-0650-9

Kolleck, A. (2021). Does Car-Sharing Reduce Car Ownership? Empirical Evidence from Germany. *Sustainability*, *13*(13), 7384. https://doi.org/10.3390/su13137384

Le Quéré, C., Andrew, R. M., Friedlingstein, P., Zaehle, S., & Zheng, B. (2018). Global CO2 emissions rise again in 2018 according to latest data. *Earth System Science Data*. https://doi.org/10.5194/essd-10-2141-2018

Leslie, N. (2014). *Full-Fuel-Cycle Energy and Emission Factors for Building Energ ay Consumption – 2013 Update* (Issue January).

Lettenmeier, Michael., Rohn, H., Liedtke, C., & Schmidt-Bleek, F. (2009). Resource productivity in 7 steps How to develop eco-innovative products and services and improve their material footprint. *Wuppertal Spezial*.

Loepp, E., & Kelly, J. T. (2020). Distinction without a difference? An assessment of MTurk Worker types. *Research and Politics*, *7*(1), 205316801990118. https://doi.org/10.1177/2053168019901185

Luo, H., Kou, Z., Zhao, F., & Cai, H. (2019). Comparative life cycle assessment of station-based and dock-less bike sharing systems. *Resources, Conservation and Recycling*. https://doi.org/10.1016/j.resconrec.2019.03.003

Lyon, T. P., & Montgomery, A. W. (2015). The Means and End of Greenwash. *Organization & Environment*, *28*(2), 223–249. https://doi.org/10.1177/1086026615575332

Magnier, L., & Mugge, R. (2022). *Replaced too soon? An exploration of Western European consumers' replacement of electronic products*. https://doi.org/10.1016/j.resconrec.2022.106448

Maitre-Ekern, E., & Dalhammar, C. (2016). Regulating planned obsolescence: A review of legal approaches to increase product durability and reparability in Europe. In *Review of European, Comparative and International Environmental Law* (Vol. 25, Issue 3, pp. 978–394). https://doi.org/10.1111/reel.12182

Makov, T., & Font Vivanco, D. (2018). Does the Circular Economy Grow the Pie? The Case of Rebound Effects From Smartphone Reuse. *Frontiers in Energy Research*, *6*(May), 39. https://doi.org/10.3389/fenrg.2018.00039

Martin, E., & Shaheen, S. (2011). The impact of carsharing on public transit and non-motorized travel: An exploration of North American carsharing survey data. *Energies*, *4*(11), 2094–2114. https://doi.org/10.3390/en4112094

Martin, E., & Shaheen, S. (2016). *Impacts of Car2Go on Vehicle Ownership, Modal Shift, Vehicle Miles Traveled, and Greenhouse Gas Emissions: An Analysis of Five North American Cities*.

Martin, E., Shaheen, S., & Lidicker, J. (2010). Impact of Carsharing on Household Vehicle Holdings. *Transportation Research Record: Journal of the Transportation Research Board*, *2143*, 150–158. https://doi.org/10.3141/2143-19

Matsumoto, M., Clemm, C., Awazu H, & Tominaga, J. (2023, May). *Mobile phone reuse businesses in Japan and an estimation of their environmental load reduction effects*.

Mattia, G., Guglielmetti Mugion, R., & Principato, L. (2019). Shared mobility as a driver for sustainable consumptions: The intention to re-use free-floating car sharing. In *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2019.06.235

Meijkamp, R. (1998). *Changing Consumer Behaviour Through Eco-Efficient Services: An Empirical Study Of Car Sharing In The Netherlands*. *244*, 234–244. https://doi.org/10.1002/(SICI)1099-0836(199809)7:4<234::AID-BSE159>3.0.CO;2-A

Meshulam, T., Goldberg, S., Ivanova, D., & Makov, T. (2024). The sharing economy is not always greener: a review and consolidation of empirical evidence. In *Environmental Research Letters* (Vol. 19, Issue 1, p. 013004). IOP Publishing. https://doi.org/10.1088/1748-9326/ad0f00

Mitropoulos, L., & Prevedouros, P. (2014). Multicriterion Sustainability Assessment in Transportation. *Transportation Research Record: Journal of the Transportation Research Board*, *2403*, 52–61. https://doi.org/10.3141/2403-07

Mont, O. (2002). Clarifying the concept of product–service system. *Journal of Cleaner Production*, *10*(3), 237–245. https://doi.org/10.1016/S0959-6526(01)00039-7

Mont, O. (2004). Institutionalisation of sustainable consumption patterns based on shared use. *Ecological Economics*, *50*(1–2), 135–153. https://doi.org/10.1016/j.ecolecon.2004.03.030

Moon, D., Kurisu, K., & Tahara, K. (2023). Which products are bought second-hand and by whom?: Analysis of consumer-preferred acquisition modes by product type. *Resources, Conservation and Recycling*, *190*(December 2022), 106860. https://doi.org/10.1016/j.resconrec.2022.106860

Mostert, C., & Bringezu, S. (2019). Measuring product material footprint as new life cycle impact assessment method: Indicators and abiotic characterization factors. *Resources*. https://doi.org/10.3390/resources8020061

Murakami, S., Oguchi, M., Tasaki, T., Daigo, I., & Hashimoto, S. (2010). Lifespan of commodities, part I: The creation of a database and its review. *Journal of Industrial Ecology*, *14*(4), 598–612. https://doi.org/10.1111/j.1530-9290.2010.00250.x

Mutel, C. (2017). Brightway: An open source framework for Life Cycle Assessment. *The Journal of Open Source Software*. https://doi.org/10.21105/joss.00236

Nakamura, S., Kondo, Y., Matsubae, K., Nakajima, K., & Nagasaka, T. (2011). UPIOM: A new tool of mfa and its application to the flow of iron and steel associated with car production. *Environmental Science and Technology*, *45*(3), 1114–1120. https://doi.org/10.1021/es1024299

Nakamura, S., & Nakajima, K. (2005). Waste input-output material flow analysis of metals in the japanese economy. *Materials Transactions*, *46*(12), 2550–2553. https://doi.org/10.2320/matertrans.46.2550

Namazu, M., & Dowlatabadi, H. (2018). Vehicle ownership reduction: A comparison of one-way and two-way carsharing systems. *Transport Policy*, *64*(November 2017), 38–50. https://doi.org/10.1016/j.tranpol.2017.11.001

Nasr, N., Russell, J., Bringezu, S., Hellweg, S., Hilton, B., Kreiss, C., & von Gries, N. (2018). Redefining Value the Manufacturing Revolution. In *International Resource Panel*. https://doi.org/10.13140/RG.2.2.31020.00640

National Energy Board of Canada. (2016). Canada's Energy Future 2016: Province and Territory Outlooks. *National Energy Board*, 58. https://doi.org/ISSN 2369-1479

Nazzal, D., Batarseh, O., Patzner, J., & Martin, D. R. (2013). Product servicing for lifespan extension and sustainable consumption: An optimization approach. *International Journal of Production Economics*, *142*(1), 105–114. https://doi.org/10.1016/j.ijpe.2012.10.017

Nicholson, W., & Snyder, C. (2005). Microeconomic Theory: Basic Principles and Extensions. In *Microeconomic theory: Basic principles and extensions*.

Nijland, H., & van Meerkerk, J. (2017). Mobility and environmental impacts of car sharing in the Netherlands. *Environmental Innovation and Societal Transitions*, *23*, 84–91. https://doi.org/10.1016/j.eist.2017.02.001

OECD. (2008). Measuring Material Flows and Resource Productivity. *Volume 1*, *III*, 1–164.

Oguchi, M., & Daigo, I. (2017). Measuring the historical change in the actual lifetimes of consumer durables. *PRODUCT LIFETIMES AND THE ENVIRONMENT (PLATE)*, 319–323.

Oguchi, M., & Fuse, M. (2015). Regional and longitudinal estimation of product lifespan distribution: A case study for automobiles and a simplified estimation method. *Environmental Science and Technologym*, *49*(3), 1738–1743. https://doi.org/10.1021/es505245q

Oguchi, M., Murakami, S., Sakanakura, H., Kida, A., & Kameya, T. (2011). A preliminary categorization of end-of-life electrical and electronic equipment as secondary metal resources. *Waste Management*, *31*(9–10), 2150–2160. https://doi.org/10.1016/j.wasman.2011.05.009

Oguchi, M., Murakami, S., Tasaki, T., Daigo, I., & Hashimoto, S. (2010). Lifespan of commodities, part II: Methodologies for estimating lifespan distribution of commodities. *Journal of Industrial Ecology*. https://doi.org/10.1111/j.1530-9290.2010.00251.x

Oguchi, M., Tasaki, T., Terazono, A., & Nishijima, D. (2019). A Product Lifetime Model for Assessing the Effect of Product Lifetime Extension Behavior by Different Consumer Segments. *PLATE – Product Lifetimes And The En- Vironment : Proceedings, 3rd PLATE CONFERENCE, BERLIN, GERMANY*. https://doi.org/10.14279/depositonce-9253

Ohno, H., Sato, H., & Fukushima, Y. (2018). Configuration of Materially Retained Carbon in Our Society: A WIO-MFA-Based Approach for Japan. *Environmental Science and Technology*, *52*(7), 3899–3907. https://doi.org/10.1021/acs.est.7b06412

O'Neill, D. W., Fanning, A. L., Lamb, W. F., & Steinberger, J. K. (2018). A good life for all within planetary boundaries. *Nature Sustainability*, *1*(2), 88–95. https://doi.org/10.1038/s41893-018-0021-4

Ottelin, J., Heinonen, J., & Junnila, S. (2017). Rebound effects for reduced car ownership and driving. *Nordic Experiences of Sustainable Planning: Policy and Practice*, *August*, 263–283. https://doi.org/10.4324/9781315598529

Pamminger, R., Glaser, S., & Wimmer, W. (2021). Modelling of different circular end-of-use scenarios for smartphones. *International Journal of Life Cycle Assessment*, *26*(3), 470–482. https://doi.org/10.1007/s11367-021-01869-2

Parguel, B., Lunardo, R., & Benoit-Moreau, F. (2017). Sustainability of the sharing economy in question: When second-hand peer-to-peer platforms stimulate indulgent consumption. *Technological Forecasting and Social Change*, *125*, 48–57. https://doi.org/10.1016/j.techfore.2017.03.029

Passer, A., Lasvaux, S., Allacker, K., De Lathauwer, D., Spirinckx, C., Wittstock, B., Kellenberger, D., Gschösser, F., Wall, J., & Wallbaum, H. (2015). Environmental product declarations entering the building sector: critical reflections based on 5 to 10 years experience in different European countries. In *International Journal of Life Cycle Assessment*. https://doi.org/10.1007/s11367-015-0926-3

Proposal for a Directive on common rules promoting the repair of goods. (2023). European Commission. https://commission.europa.eu/document/afb20917-5a6c-4d87-9d89-666b2b775aa1_en

Proposal for a Directive on Green Claims. (2023). European Commission. https://environment.ec.europa.eu/publications/proposal-directive-green-claims_en

Proske, M. (2022). How to address obsolescence in LCA studies – Perspectives on product use-time for a smartphone case study. *Journal of Cleaner Production*, *376*, 134283. https://doi.org/10.1016/j.jclepro.2022.134283

Rabbitt, N., & Ghosh, B. (2016). Economic and environmental impacts of organised Car Sharing Services: A case study of Ireland. *Research in Transportation Economics*. https://doi.org/10.1016/j.retrec.2016.10.001

Raworth, K. (2017). *Doughnut economics: Seven ways to think like a 21st-century economist*. Chelsea Green Publishing.

Rene, E. R., Sethurajan, M., Kumar Ponnusamy, V., Kumar, G., Ngoc, T., Dung, B., Brindhadevi, K., & Pugazhendhi, A. (2021). *Electronic waste generation, recycling and resource recovery: Technological perspectives and trends*. https://doi.org/10.1016/j.jhazmat.2021.125664

Saunders, H. D. (2000). A view from the macro side: Rebound, backfire, and Khazzoom-Brookes. *Energy Policy*, *28*(6–7), 439–449. https://doi.org/10.1016/S0301-4215(00)00024-0

Saurat, M., & Ritthoff, M. (2013). Calculating MIPS 2.0. *Resources*. https://doi.org/10.3390/resources2040581

Scarinci, R., Rast, F., & Bierlaire, M. (2017). Needed reduction in mobility energy consumption to meet the goal of a 2000-watt society. *Transportation Research Part A: Policy and Practice*. https://doi.org/10.1016/j.tra.2017.05.010

Schlomer, S., Bruckner, T., Fulton, L., Hertwich, E., McKinnon, A., Perczyk, D., Roy, J., Schaeffer, R., Sims, R., Smith, P., & Wiser, R. (2014). Annex III: Technology-Specific Cost and Performance Parameters. In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. https://doi.org/https://doi.org/10.1017/CBO9781107415416.025

Schmidt-Bleek, F. (1994). MIPS: Ein neues ökologisches Maß. In *Wieviel Umwelt braucht der Mensch?* (pp. 97–141). Birkhäuser Basel. https://doi.org/10.1007/978-3-0348-5650-8_4

Schor, J. (2014). Debating the Sharing Economy. *Journal of Self-Governance & Management Economics*. https://doi:10.22381/JSME4320161

Shaheen, S., Cohen, A., & Jaffee, M. (2018). Innovative Mobility: Carsharing Outlook. CArsharing market overview, analysis and trends. In *Transportation Sustainability Research Center - University of California, Berkeley*. https://doi.org/10.7922/G2CC0XVW

Shaheen, S., Martin, E., & Bansal, A. (2018). Peer-To-Peer (P2P) Carsharing: Understanding Early Markets, Social Dynamics, and Behavioral Impacts. In *UC Berkeley Research Report*. https://doi.org/10.7922/G2FN14BD

Sims, R., Schaeffer, R., Creutzig, F., Cruz-Núñez, X., D'Agosto, M., Dimitriu, D., Meza, M. J. F., Fulton, L., Kobayashi, S., Lah, O., McKinnon, A., Newman, P., Ouyang, M., Schauer, J. J., Sperling, D., & Tiwari, G. (2014). *Transport. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovern- mental Panel on Climate Change*. https://doi.org/10.1016/j.rser.2011.05.001

Singh, J., & Ordoñez, I. (2016). Resource recovery from post-consumer waste: important lessons for the upcoming circular economy. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2015.12.020

Sorrell, S. (2007). The rebound effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency. In *Australian family physician* (Vol. 42, Issue 4). https://doi.org/1-903144-0-35

Stahel, W. R. (2016). The circular economy. *Nature*, *531*(7595), 435–438. https://doi.org/10.1038/531435a

Statistics Netherlands. (2016). *Transport and Mobility 2016*.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., De Vries, W., De Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, *347*(6223). https://doi.org/10.1126/science.1259855

Steffens, P. R. (2001). An aggregate sales model for consumer durables incorporating a time-varying mean replacement age. *Journal of Forecasting*, *20*(1), 63–77. https://doi.org/10.1002/1099-131X(200101)20:1<63::AID-FOR758>3.0.CO;2-D

Steubing, B., de Koning, D., Haas, A., & Mutel, C. L. (2020). The Activity Browser — An open source LCA software building on top of the brightway framework. *Software Impacts*. https://doi.org/10.1016/j.simpa.2019.100012

Stigson, B., Madden, K., Young, R., Brady, K., & Hall, J. (2006). Eco-efficiency Learning Module. *World Business Council for Sustainable Development(WBCSD)*, 231.

Suzuki, K., Alam, M. M., Yoshikawa, T., & Yamamoto, W. (2008). Two methods for estimating product lifetimes from only warranty claims data. *Proceedings - The 2nd IEEE International Conference on Secure System Integration and Reliability Improvement, SSIRI 2008*. https://doi.org/10.1109/SSIRI.2008.59

Tecchio, P., Ardente, F., & Mathieux, F. (2019). Understanding lifetimes and failure modes of defective washing machines and dishwashers. *Journal of Cleaner Production*, *215*, 1112–1122. https://doi.org/10.1016/j.jclepro.2019.01.044

Teehan, P., & Kandlikar, M. (2013). Comparing embodied greenhouse gas emissions of modern computing and electronics products. *Environmental Science and Technology*, *47*(9), 3997–4003. https://doi.org/10.1021/es303012r

Temenos, C., Nikolaeva, A., Schwanen, T., Cresswell, T., Sengers, F., Watson, M., & Sheller, M. (2017). Theorizing Mobility Transitions: An Interdisciplinary Conversation. *Transfers*, *7*(1), 113–129. https://doi.org/10.3167/TRANS.2017.070109

*The World Factbook 2021*. (2021). Washington, DC: Central Intelligence Agency.

Thiébaud-Müller, E., Hilty, L. M., Schluep, M., Widmer, R., & Faulstich, M. (2018). Service Lifetime, Storage Time, and Disposal Pathways of Electronic Equipment: A Swiss Case Study. *Journal of Industrial Ecology*, *22*(1), 196–208. https://doi.org/10.1111/jiec.12551

Thomas, B. A., & Azevedo, I. L. (2013). Estimating direct and indirect rebound effects for U.S. households with input–output analysis Part 1: Theoretical framework. *Ecological Economics*, *86*, 199–210. https://doi.org/10.1016/j.ecolecon.2012.12.003

Tukker, A. (2004). Eight types of product–service system: eight ways to sustainability? Experiences from SusProNet. *Business Strategy and the Environment*, *13*(4), 246–260. https://doi.org/10.1002/bse.414

Tukker, A., Huppes, G., Guinee, J., Heijungs, R., de Koning, A., van Oers, L., Suh, S., Geerken, T., van Holderbeke, M., Jansen, B., & Nielsen, P. (2006). Environmental Impact of Products ( EIPRO ): Analysis of the life cycle environmental impacts related to the final consumption of the EU25. In *Institute for Prospective Technological Studies: Vol. EUR 22284* (Issue May).

UNEP. (2021). *The use of natural resources in the economy: A Global Manual on Economy Wide Material Flow Accounting*.

U.S. EPA. (2008). Elaectronics waste management in the united states: Approach 1. In *U.S. EPA*.

van Loon, P., Delagarde, C., & Van Wassenhove, L. N. (2018). The role of second-hand markets in circular business: a simple model for leasing versus selling consumer products. *International Journal of Production Research*, *56*(1–2), 960–973. https://doi.org/10.1080/00207543.2017.1398429

van Nes, N., & Cramer, J. (2006). Product lifetime optimization: a challenging strategy towards more sustainable consumption patterns. *Journal of Cleaner Production*, *14*(15–16), 1307–1318. https://doi.org/10.1016/j.jclepro.2005.04.006

Vendrell-Herrero, F., Vaillant, Y., Bustinza, O. F., & Lafuente, E. (2021). Product lifespan: the missing link in servitization. *Production Planning & Control*, 1–17. https://doi.org/10.1080/09537287.2020.1867773

Wäger, P. A., Hischier, R., & Widmer, R. (2015). *The Material Basis of ICT Patrick*. *310*. https://doi.org/10.1007/978-3-319-09228-7

Warmington-Lundström, J., & Laurenti, R. (2020). Reviewing circular economy rebound effects: The case of online peer-to-peer boat sharing. *Resources, Conservation & Recycling: X*, *5*, 100028. https://doi.org/10.1016/j.rcrx.2019.100028

Webster's. (1971). seventh new collegiate dictionary. In *Webster's Third New International Dictionary*.

Wells, P. (2018). Degrowth and techno-business model innovation: The case of Riversimple. *Journal of Cleaner Production*, *197*, 1704–1710. https://doi.org/10.1016/j.jclepro.2016.06.186

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *International Journal of Life Cycle Assessment*. https://doi.org/10.1007/s11367-016-1087-8

Weymar, E., & Finkbeiner, M. (2016). Statistical analysis of empirical lifetime mileage data for automotive LCA. *International Journal of Life Cycle Assessment*, *21*(2), 215–223. https://doi.org/10.1007/s11367-015-1020-6

*Which?* (2022). https://www.which.co.uk/

Wiedmann, T. O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., & Kanemoto, K. (2015). The material footprint of nations. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(20), 6271–6276. https://doi.org/10.1073/PNAS.1220362110/-/DCSUPPLEMENTAL

Wiesen, K., Saurat, M., & Lettenmeier, M. (2014). Calculating the Material Input per Service Unit using the Ecoinvent database. *International Journal of Performability Engineering*, *10*(4), 357–366.

Wieser, H., & Tröger, N. (2016). Exploring the inner loops of the circular economy: Replacement, repair, and reuse of mobile phones in Austria. *Journal of Cleaner Production*, *172*, 3042–3055. https://doi.org/10.1016/j.jclepro.2017.11.106

Williams, E. D., Ayres, R. U., & Heller, M. (2002). The 1.7 Kilogram Microchip: Energy and Material Use in the Production of Semiconductor Devices. *Environmental Science & Technology*, *36*(24), 5504–5510. https://doi.org/10.1021/es025643o

Wilson, G. T., Smalley, G., Suckling, J. R., Lilley, D., Lee, J., & Mawle, R. (2017). The hibernating mobile phone: Dead storage as a barrier to efficient electronic waste recovery. *Waste Management*, *60*, 521–533. https://doi.org/10.1016/J.WASMAN.2016.12.023

Woidasky, J., & Cetinkaya, E. (2021). Use pattern relevance for laptop repair and product lifetime. *Journal of Cleaner Production*, *288*, 125425. https://doi.org/10.1016/J.JCLEPRO.2020.125425

WWF. (2022). Living planet report 2022: Building a nature-positive society. In *A Banson Production, …*.

Wynes, S., & Nicholas, K. A. (2017). The climate mitigation gap: education and government recommendations miss the most effective individual actions. *Environmental Research Letters*, *12*(7), 074024. https://doi.org/10.1088/1748-9326/aa7541

York, R., & McGee, J. A. (2016). Understanding the Jevons paradox. *Environmental Sociology*, *2*(1), 77–87. https://doi.org/10.1080/23251042.2015.1106060

Zerbino, P. (2022). How to manage the Circular Economy Rebound effect: A proposal for contingency-based guidelines. *Journal of Cleaner Production*, *378*, 134584. https://doi.org/10.1016/j.jclepro.2022.134584

Zhang, K., Schnoor, J. L., & Zeng, E. Y. (2012). E-waste recycling: Where does it go from here? *Environmental Science and Technology*, *46*(20), 10861–10867. https://doi.org/10.1021/es303166s

Zhou, F., Zheng, Z., Whitehead, J., Perrons, R. K., Washington, S., & Page, L. (2020). Examining the impact of car-sharing on private vehicle ownership. *Transportation Research Part A: Policy and Practice*, *138*, 322–341. https://doi.org/10.1016/j.tra.2020.06.003

Zink, T., & Geyer, R. (2017). Circular Economy Rebound. *Journal of Industrial Ecology*, *21*(3), 593–602. https://doi.org/10.1111/jiec.12545

Zink, T., Maker, F., Geyer, R., Amirtharajah, R., & Akella, V. (2014). Comparative life cycle assessment of smartphone reuse: repurposing vs. refurbishment. *The International Journal of Life Cycle Assessment*, *19*(5), 1099–1109. https://doi.org/10.1007/s11367-014-0720-7

# Curriculum Vitae

Levon Amatuni was born on November 27, 1990, in Moscow, USSR. He studied at Gymnasium No. 1567 and then at the mathematics class at High School No. 91. Levon obtained a Specialist Diploma (equivalent to a Master's Degree) in Computer Science from Lomonosov Moscow State University in 2014, specializing in Numerical Methods. Later, after moving his life to Canada, Levon earned another Master's Degree from the University of Toronto in 2019, focusing on Sustainability Informatics at the Department of Computer Science, supervised by Prof. Dr. Steve Easterbrook.
For his PhD, Levon moved to the Netherlands, where he worked on a global supply chain database for critical metals and researched the impacts of sustainable consumption practices, under the supervision of Dr. José Mogollón and Prof. Dr. Arnold Tukker. Since the end of 2023, Levon has held a postdoctoral position working on an ESED project at TU Delft and also, for 1day per week, Levon conducts research for the CE-RISE project at CML at Leiden University.

# Publications


- Amatuni, L., Steubing, B., Heijungs, R., Yamamoto, T., & Mogollón, J. M. (2024). Deriving material composition of products using life cycle inventory databases. *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.13538

- Amatuni, L., Yamamoto, T., Baldé, C. P., Clemm, C., & Mogollón, J. M. (2023). Quantifying total lifetimes of consumer products: Stochastic modelling accounting for second-hand use and establishing an open-collaborative database. *Resources, Conservation and Recycling*, 197, 107103. https://doi.org/10.1016/j.resconrec.2023.107103

- Amatuni, L., Ottelin, J., Steubing, B., & Mogollón, J. M. (2020). Does car sharing reduce greenhouse gas emissions? Assessing the modal shift and lifetime shift rebound effects from a life cycle perspective. *Journal of Cleaner Production*, *266*, 121869. https://doi.org/10.1016/j.jclepro.2020.121869

# Supplementary materials

## Related to Chapter 2

### Appendix A: Life cycle inventory

Emissions factors for car (including CS), bus, and rail used in this study are obtained using those from the study by Chester (2008). Out all of the life cycle stages considered in the original study, only the major ones, which would contribute to at least 90% of the total emissions factor have been selected for various modes (see Tables A.1 – A.3).

**Table A.1** LCI (life-cycle inventory) for regular sedan gasoline car (Toyota Camry)used in our study given emissions factors from the original study: (Chester, 2008); VKT = vehicle km travelled

| LCAI | Emissions factor (kg $CO_2$e /VKT) | Life-cycle component |
|---|---|---|
| Infrastructure construction | 14000 / $LTM_{car}$ | Roadway Construction |
| Vehicle manufacturing | 8500 / $LTM_{car}$ | Manufacturing |
| Fuel production | 0.038 | Refining & Distribution |
| Vehicle operation | 0.230 | Operation (Running) |

**Table A.2** LCI (life-cycle inventory) for a gasoline 40-foot bus (US)used in our study given emissions factors from the original study: (Chester, 2008); VKT = vehicle km travelled

| LCAI | Emissions factor (kg $CO_2$e /VKT) | Life-cycle component |
|---|---|---|
| Infrastructure construction | 0.042 | Roadway Construction |
| Vehicle manufacturing | 0.199 | Manufacturing |
| Fuel production | 0.236 | Refining & Distribution |
| Vehicle operation | 1.491 | Operation (Running) |

**Table A.3** LCI (life-cycle inventory) for urban rail used in our study given emissions factors of the Green Line Vehicle (Boston, US) from the original study: (Chester, 2008). MJ = megajoule, VKT = vehicle km travelled

| LCAI | Emissions factor per VKT | Life-cycle component |
|---|---|---|
| Infrastructure construction | 1.081 kg $CO_2e$ | Station Construction; Track/Power Construction |
| Infrastructure operation | 8.9 MJ | Station Lighting; Station Escalators; Station Train Control; Station Parking Lighting; Station Miscellaneous |
| Vehicle manufacturing | 0.038 kg $CO_2e$ | Manufacture |
| Vehicle operation | 30 MJ | Operation (Active); Operation (Idling); Operation (HVAC) |

Later, for our study, these have been adjusted given occupancy rates and automobiles' LTMs in our study to obtain total per-PKT emissions factors instead.

Emissions factor for cycling has been taken from the study by Blondel et al. (2011), and that covers all of the four stages considered for the previous modes except the infrastructure-related emissions which were considered as zero in this study.

## Appendix B: Energy life cycle emissions factors

The emissions behind infrastructure and vehicle operations are dependent on a particular energy source profile in the region of operation. For the Canadian provinces of Alberta (AL) this is reported by the National Energy Board of Canada (2016), for the Netherlands (NL) by the Energie Beheer Nederland (2018). See Table B.1.

**Table B.1** Energy sources profiles. Sources: NEB Canada, EBN Nederland

| Province | Uranium | Coal | Hydro | Natural Gas | Wind | Solar | Biomass | Petroleum |
|---|---|---|---|---|---|---|---|---|
| AL | - | 47% | 3% | 40% | 7% | - | 3% | - |
| NL | 1% | 14% | - | 40% | 1% | 1% | 4% | 39% |

Given the energy sources profile for a particular region, the following full life-cycle emissions factors for energy production and distribution by different energy sources are used to calculate the average emissions factor for each region (Schlomer et al., 2014). Petroleum's emissions were not found and were taken as for the biomass (Table B.2).

**Table B.2** Full-fuel-cycle electricity emissions factors. Source: Schlomer et al., 2014

| | Nuclear | Coal | Hydro | Natural Gas | Wind | Solar | Biomass | Petroleum |
|---|---|---|---|---|---|---|---|---|
| gCO2eq /kWh | 12 | 820 | 24 | 490 | 11 | 44 | 230 | 230 |

As a result of multiplying these two data sets, the average emissions factor for Alberta weighted by its energy profile is 590 gCO2 eq. per a kWh of energy used. For the Netherlands this comes to 410 gCO2 eq per kWh of energy.

For the US states, energy life-cycle emissions are taken from the previous report (Leslie, 2014): 538 gCO2 eq for a kWh of energy produced in Massachusetts, 327 gCO2 eq in California, 39 gCO2 eq in Vermont, 1397 gCO2 eq in Washington D.C., and 157 gCO2 eq in Washington state.

## Appendix C: Region-specific calculations

### Netherlands

First, the total annual transportation distance of 11,000 km was assumed as it has been reported for an average Dutch citizen (Statistics Netherlands, 2016). Next, the modal preference profile reported by CS participants (Table C.1) has been used to estimate not only distances travelled by an average member before participation (instead of CS driving) but to estimate distances travelled by alternative modes as total driving decreases after participation as well. This was done, first, redistributing the non-driving 'before' distances between other modes proportionally to the preference profile and, secondly, redistributing the annual distance gap between the 'after' alternative modes ('before' and 'after' distances in Table 2.2). As a result, total annual distances are not equal because of the effect of the 'would not be travelled' option in the surveyed preference profile. Next, differences in the total distances travelled by each mode were calculated and multiplied by the corresponding per-PKT emission factors to estimate the total annual reduction in emissions caused by CS participation (Table 2.2).

**Table C.1** Car-sharing substitution in the absence of the CS service in the Netherlands. Here, we assumed 'bus' distances as 4% and 'rail' distances as 41% from the original study. Source: (Nijland & van Meerkerk, 2017)

| Mode of transport | Kilometres (in %) |
|---|---|
| Car | 34 |
| Train | 41 |
| Bus, tram, rapid transit | 4 |
| Bicycle | 3 |
| Car passenger | 1 |
| Other | 2 |
| Not travelled | 15 |

Here, rail per-PKT emissions were recalculated using the appropriate electricity emissions factor for the Netherlands. Car passenger (ride-sharing or carpooling) per-PKT emissions were taken as regular car emissions adjusted for occupancy of 2.5 rather than 1.58. Per-PKT emissions for 'other' were averaged across other modes and halved to account for walking (zero emissions). Car-sharing per-PKT emissions were set as a range based on the three CS lifetime mileage scenarios.

Even though the Dutch study considers both B2C and peer-to-peer (P2P) participation and covers the country rather than the city level, the authors report that the difference between B2C and P2C in terms of the 'before-and-after' change in driving is not significant. Moreover, in practice, B2C platforms are placed in the urban areas.

<u>San Francisco</u>

Data (several distances and the percentage changes) reported by the original study allows to estimate the total annual 'after' and, consequentially, 'after' rail distances. The rest of the 'after' modes are estimated redistributing the rest of the total distance between other modes using reported preference profile (Table C.2 of this supplementary). Afterward, the 'before' car-VKT could be estimated using the reported decrease rate. Finally, the before-and-after annual distance gap would be redistributed to the 'before' distances of the rest of the modes according to the same preference profile. These were used to estimate before-and-after distances for all the modes using the surveyed modal preference profile to redistribute annual distance gap between unknown distances by alternative modes. Resulting changes in annual distances are in turn multiplied by the per-PKT emission factors of the corresponding modes to obtain total emissions change for each transport mode. Per-PKT emissions for 'other' were averaged across other modes.

**Table C.2** Car-sharing substitution in the absence of the City CarShare service in San Francisco. Here, 'car' mode aggregates originally reported on-road modes, and the reported public transportation distance has been split equally into 'train' and 'bus' modes as they have not been distinguished. Source: (Cervero et al., 2007)

| Mode of transport | Kilometres (in %) |
|---|---|
| Car | 27.3 |
| Train | 14.3 |
| Bus, tram, rapid transit | 14.3 |
| Bicycle | 3.9 |
| Walking | 6.9 |
| Other | 3.2 |
| Not travelled | 30.1 |

<u>Calgary</u>

Given driving distances for the 'before' period, distances for the rest of the 'before' modes are estimated proportionally to the existing official figures on a complete modal breakdown in Calgary (Behan & Lea, 2014), see Table C.3. Next, the resulting before-and-after total distance gap was redistributed between the alternative modes in the 'after' period according to the same profile. This allowed accounting for a change in modal distances caused by CS participation ('before' and 'after' distances in Table 2.4). Per-PKT emissions for 'other' mode were averaged across other modes. Life-cycle electricity-related emissions factor for the province of Alberta in Canada was used (see Appendix D).

**Table C.3** Modal breakdown for Calgary. Numbers are rounded based on the original source. The reported public transportation ration has been split equally into 'train' and 'bus' modes as they have not been distinguished. 'Walk and bicycle' mode has been equally split into two separate modes as well. Source: (Behan & Lea, 2014)

| Mode of transport | Kilometres (in %) |
|---|---|
| Car | 76 |
| Train | 8 |
| Bus | 8 |
| Bicycle | 4 |
| Walking | 4 |

## Appendix D: Lifetime mileage analysis

A correlation between end of life vehicle (ELV) state of a vehicle and the total mileage or the life time parameters would suggest that these parameters could predict the ELV state, hence allowing to estimate the LTM of shared vehicles given the intensity of their use.

For this purpose, the UK's periodic technical inspection (MOT) vehicle database has been analysed. This database allows to track the same vehicle using their unique vehicle IDs from 2013 to 2015. As soon as a vehicle appeared at the test for 2013, failed it for that year, and never appeared back for the test within next two years in the database, the vehicle was considered to be discarded. It was shown in a similar study that such an approach mitigates distortions because of the crashed or exported vehicles (Dun et al., 2015).

In total, 156,838 ELVs were extracted from the 2013 dataset with an average age of 14.7 years and average mileage of 173,000 km. These data were balanced with non-ELVs from the same year to prepare for a logistic regression analysis. In particular, two models with one independent parameter each were assessed - the age and the mileage of the vehicle, to predict the vehicle's end-of-life status.

As a result (Table D.1), even though both parameters had a statistically significant positive relationship with the ELV status (positive regressions coefficients and P-values lower than 0.05), none of them explained the variance of the dependent variable well enough (very low pseudo R-squared values).

**Table D.1** Logistic regression analysis results. ELV binary status – as a dependent variable. The age or the total mileage are the independent variables for two models.

| Model | Coef. | Std. err. | z | P | Pseudo R2 |
|---|---|---|---|---|---|
| age | 0.0329 | 0.0029 | 11.5040 | 0.0000 | 0.03 |
| mileage (1000 km) | 0.0022 | 0.0002 | 9.5918 | 0.0000 | 0.02 |

Such results do not allow to prove any hypothesis about explanatory power of the age and mileage for the end-of-life of the automobile.

## Appendix E: Car2Go fleet lifetime mileage

Table E.1 depicts the fleet sizes (Car2Go: Pioneer And Market Leader In Free-Floating Carsharing, 2017) and the total annual Car2Go mileage for each city (Martin & Shaheen, 2016).

**Table E.1** Estimating car-sharing fleet's lifetime mileage-based Car2Go data for four cities. VKT = Vehicle kilometres travelled. Distance units have been made converted to km.

| | Calgary | Seattle | Vancouver | Washington D.C | Average |
|---|---|---|---|---|---|
| Total VKT (annual, km) | 8 400 000 | 9 900 000 | 9 108 000 | 14 700 000 | |
| Fleet size | 630 | 750 | 1275 | 600 | |
| Mileage (annual, km) | 13 300 | 13 100 | 11 500 | 9 700 | 11 900 |

A recent Car2Go press release reported 90 million kilometres driven by 14,000 Car2Go vehicles in 6 months (Car2Go: Press Release, 2018). This translates to the 12900 km in annual mileage for car-sharing vehicles. Thus, combining this with the average result from the Table E.1, it could be assumed for this scenario that relatively lower annual distances (12200 km) are driven by the shared automobiles during the same lifetime (15 years).

## Appendix F: Existing misalignments

Interestingly, the Dutch study assumed a constant 15 years lifetime for shared and private vehicles and the LTM of 250,000 km (Nijland & van Meerkerk, 2017) for the manufacturing emissions calculations; however, it quantifies vehicle's manufacturing emissions indirectly based on a study with a very different automobile LTM assumed, namely 150,000 km (Nijland & van Meerkerk, 2017). If calculated given the corresponding LTM, the reduction in manufacturing emissions in their study would drop from the proposed 125-281 to 142-186 kg $CO_2$-eq per year. This exemplifies how sensitive the total results are to the LTM assumptions, and suggests another explanation for the lower emission savings from CS in this study.

Nijland and van Meerkerk (2017) mistakenly multiply the average amount of the reduced vehicles per average CS member (-0.4) caused by participation by the shared car 'ownership' (1/15 portion of the shared vehicle from the platform) instead of adding these numbers. Technically, the overall vehicle ownership change after selling the vehicle and 'owning' a portion of the CS fleet has to be: -0.4 + 1/15 = -0.3(3). Moreover, their study quantifies vehicle's manufacturing emissions indirectly through their proposed LTM (250 000 km) based on another study (Gbeghaje-Das, E., 2013) with a very different LTM assumed (150 000 km). Accounting for only these two last misconceptions, the reductions in manufacturing emissions drop from the proposed 125-281 to 142-186 kg CO2e per year which is an enormous difference relative to their final results of 236–392 kg CO2e per year reduction for the average car-sharing member.

## Appendix G: Private vehicle's lifetime mileage estimation

**Table G.1** Lifetime and lifetime mileage for an average private automobile in the USA. Reported by different studies and their average. Distance units have been made converted to km.

| Source | Age (years) | Annual mileage (km) | $LTM_{car}$ (km) |
|---|---|---|---|
| (Mitropoulos & Prevedouros, 2014) | 10.6 | 18 100 | 192000 |
| (Martin et al., 2010) | 17.3 | 12 300 | 213 000 |
| (Chester, 2008) | 16.9 | 17 600 | 298 000 |
| Average | 15.0 | 16 000 | 234 000 |

## References


Behan, K., Lea, N.S., 2014. Benchmarking Active Transportation In Canadian Cities, Clean Air Partnership.

Blondel, B., Mispelon, C., Ferguson, J., 2011. Cycle More Often 2 Cool Down The Planet! - Quantifying CO2 savings of Cycling, European Cyclists' Federation.

Car2Go: Pioneer And Market Leader In Free-Floating Carsharing [WWW Document], 2017. . Car2Go. URL https://www.car2go.com/media/data/germany/microsite-press/files/factsheet-car2go_november-2017_en.pdf (accessed 7.11.19).

Car2Go: Press Release [WWW Document], 2018. . Car2Go. URL https://www.car2go.com/media/data/germany/microsite-press/files/20180731_press-release_car2go-launches-in-chicago-and-grows-worldwide.pdf (accessed 7.11.19).

Cervero, R., Golub, A., Nee, B., 2007. City CarShare: Longer-Term Travel Demand and Car Ownership Impacts. Transp. Res. Rec. J. Transp. Res. Board 1992, 70–80. https://doi.org/10.3141/1992-09

Cervero, R., Tsai, Y., 2007. City CarShare in San Francisco, California: Second-Year Travel Demand and Car Ownership Impacts. Transp. Res. Rec. J. Transp. Res. Board. https://doi.org/10.3141/1887-14

Chen, T.D., Kockelman, K.M., 2016. Carsharing's life-cycle impacts on energy use and greenhouse gas emissions. Transp. Res. Part D Transp. Environ. 47, 276–284. https://doi.org/10.1016/j.trd.2016.05.012

Chester, M., 2008. Life-cycle environmental inventory of passenger transportation in the United States. Inst. Transp. Stud. UC Berkeley.

Chester, M. V., Horvath, A., 2009. Environmental assessment of passenger transportation should include infrastructure and supply chains. Environ. Res. Lett. 4. https://doi.org/10.1088/1748-9326/4/2/024008

Ding, N., Pan, J., Zhang, Z., Yang, J., 2019. Life cycle assessment of car sharing models and the effect on GWP of urban transportation: A case study of Beijing. Sci. Total Environ. 688, 1137–1144. https://doi.org/10.1016/j.scitotenv.2019.06.111

Dun, C., Horton, G., Kollamthodi, S., 2015. Improvements to the definition of lifetime mileage of light duty vehicles, Report for European Commission – DG Climate Action.

Energie Beheer Nederland, 2018. Energy in the Netherlands.

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in Life Cycle Assessment. J. Environ. Manage. https://doi.org/10.1016/j.jenvman.2009.06.018

Frenken, K., 2017. Sustainability perspectives on the sharing economy. Environ. Innov. Soc. Transitions 23, 1–2. https://doi.org/10.1016/j.eist.2017.04.004

Frenken, K., Meelen, T., Arets, M., van de Glind, P.B., 2015. Smarter regulation for the sharing economy [WWW Document]. Guard. URL http://www.theguardian.com/science/political-science/2015/may/20/smarter-regulation-for-the-sharing-economy (accessed 11.7.19).

Frenken, K., Waes, A. van, Smink, M., Est, R. van, 2017. A fair share – Safeguarding public interests in the sharing and gig economy, The Rathenau Instituut. The Hague.

Frost & Sullivan, 2010. Analysis of the Market for Carsharing in North America.

Grischkat, S., Hunecke, M., Böhler, S., Haustein, S., 2014. Potential for the reduction of greenhouse gas emissions through the use of mobility services. Transp. Policy. https://doi.org/10.1016/j.tranpol.2014.06.007

Hartl, B., Sabitzer, T., Hofmann, E., Penz, E., 2018. "Sustainability is a nice bonus" the role of sustainability in carsharing from a consumer perspective. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2018.08.138

Hertwich, E.G., 2005. Life cycle approaches to sustainable consumption: A critical review. Environ. Sci. Technol. 39, 4673–4684. https://doi.org/10.1021/es0497375

Hollingsworth, J., Copeland, B., Johnson, J.X., 2019. Are e-scooters polluters? the environmental impacts of shared dockless electric scooters. Environ. Res. Lett. https://doi.org/10.1088/1748-9326/ab2da8

Jones, C., Gilbert, P., Raugei, M., Mander, S., Leccisi, E., 2017. An approach to prospective consequential life cycle assessment and net energy analysis of distributed electricity generation. Energy Policy 100, 350–358. https://doi.org/https://doi.org/10.1016/j.enpol.2016.08.030

Jung, J., Koo, Y., 2018. Analyzing the effects of car sharing services on the reduction of greenhouse gas (GHG) emissions. Sustain. 10, 1–17. https://doi.org/10.3390/su10020539

Le Quéré, C., Andrew, R.M., Friedlingstein, P., Zaehle, S., Zheng, B., 2018. Global CO2 emissions rise again in 2018 according to latest data. Earth Syst. Sci. Data.

https://doi.org/10.5194/essd-10-2141-2018

Leslie, N., 2014. Full-Fuel-Cycle Energy and Emission Factors for Building Energ ay Consumption – 2013 Update.

Luo, H., Kou, Z., Zhao, F., Cai, H., 2019. Comparative life cycle assessment of station-based and dock-less bike sharing systems. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2019.03.003

Martin, E., Shaheen, S., 2016. Impacts of Car2Go on Vehicle Ownership, Modal Shift, Vehicle Miles Traveled, and Greenhouse Gas Emissions: An Analysis of Five North American Cities.

Martin, E., Shaheen, S., 2011. The impact of carsharing on public transit and non-motorized travel: An exploration of North American carsharing survey data. Energies 4, 2094–2114. https://doi.org/10.3390/en4112094

Martin, E., Shaheen, S., Lidicker, J., 2010. Impact of Carsharing on Household Vehicle Holdings. Transp. Res. Rec. J. Transp. Res. Board 2143, 150–158. https://doi.org/10.3141/2143-19

Mattia, G., Guglielmetti Mugion, R., Principato, L., 2019. Shared mobility as a driver for sustainable consumptions: The intention to re-use free-floating car sharing. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2019.06.235

Meijkamp, R., 1998. Changing Consumer Behaviour Through Eco-Efficient Services: An Empirical Study Of Car Sharing In The Netherlands 244, 234–244. https://doi.org/10.1002/(SICI)1099-0836(199809)7:4<234::AID-BSE159>3.0.CO;2-A

Mitropoulos, L., Prevedouros, P., 2014. Multicriterion Sustainability Assessment in Transportation. Transp. Res. Rec. J. Transp. Res. Board 2403, 52–61. https://doi.org/10.3141/2403-07

Mont, O., 2004. Institutionalisation of sustainable consumption patterns based on shared use. Ecol. Econ. 50, 135–153. https://doi.org/10.1016/j.ecolecon.2004.03.030

Namazu, M., Dowlatabadi, H., 2018. Vehicle ownership reduction: A comparison of one-way and two-way carsharing systems. Transp. Policy 64, 38–50. https://doi.org/10.1016/j.tranpol.2017.11.001

National Energy Board of Canada, 2016. Canada’s Energy Future 2016: Province and Territory Outlooks. Natl. Energy Board 58. https://doi.org/ISSN 2369-1479

Nijland, H., van Meerkerk, J., 2017. Mobility and environmental impacts of car sharing in the Netherlands. Environ. Innov. Soc. Transitions 23, 84–91.

https://doi.org/10.1016/j.eist.2017.02.001

Oguchi, M., Fuse, M., 2015. Regional and longitudinal estimation of product lifespan distribution: A case study for automobiles and a simplified estimation method. Environ. Sci. Technol. 49, 1738–1743. https://doi.org/10.1021/es505245q

Ottelin, J., Heinonen, J., Junnila, S., 2017. Rebound effects for reduced car ownership and driving. Nord. Exp. Sustain. Plan. Policy Pract. 263–283. https://doi.org/10.4324/9781315598529

Rabbitt, N., Ghosh, B., 2016. Economic and environmental impacts of organised Car Sharing Services: A case study of Ireland. Res. Transp. Econ. https://doi.org/10.1016/j.retrec.2016.10.001

Scarinci, R., Rast, F., Bierlaire, M., 2017. Needed reduction in mobility energy consumption to meet the goal of a 2000-watt society. Transp. Res. Part A Policy Pract. https://doi.org/10.1016/j.tra.2017.05.010

Schlomer, S., Bruckner, T., Fulton, L., Hertwich, E., McKinnon, A., Perczyk, D., Roy, J., Schaeffer, R., Sims, R., Smith, P., Wiser, R., 2014. Annex III: Technology-Specific Cost and Performance Parameters, Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. https://doi.org/https://doi.org/10.1017/CBO9781107415416.025

Schor, J., 2014. Debating the Sharing Economy. A Gt. Transit. Initiat. Essay 1–19. https://doi.org/10.7903/cmr.11116

Shaheen, S., Cohen, A., Jaffee, M., 2018a. Innovative Mobility: Carsharing Outlook. CArsharing market overview, analysis and trends, Transportation Sustainability Research Center - University of California, Berkeley. https://doi.org/10.7922/G2CC0XVW

Shaheen, S., Martin, E., Bansal, A., 2018b. Peer-To-Peer (P2P) Carsharing: Understanding Early Markets, Social Dynamics, and Behavioral Impacts, UC Berkeley Research Report. https://doi.org/10.7922/G2FN14BD

Sims, R., Schaeffer, R., Creutzig, F., Cruz-Núñez, X., D'Agosto, M., Dimitriu, D., Meza, M.J.F., Fulton, L., Kobayashi, S., Lah, O., McKinnon, A., Newman, P., Ouyang, M., Schauer, J.J., Sperling, D., Tiwari, G., 2014. Transport. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovern- mental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA. https://doi.org/10.1016/j.rser.2011.05.001

Statistics Netherlands, 2016. Transport and Mobility 2016.

Temenos, C., Nikolaeva, A., Schwanen, T., Cresswell, T., Sengers, F., Watson, M., Sheller, M., 2017. Theorizing Mobility Transitions: An Interdisciplinary Conversation. Transfers 7, 113–129. https://doi.org/10.3167/TRANS.2017.070109

Weymar, E., Finkbeiner, M., 2016. Statistical analysis of empirical lifetime mileage data for automotive LCA. Int. J. Life Cycle Assess. 21, 215–223. https://doi.org/10.1007/s11367-015-1020-6

# Related to Chapter 3

## Appendix A: Assumptions

For ownership types 2 and 3, which happen after the first second-hand reuse of the phone, the number of reports collected was noticeably lower than for ownership types 0 and 1. This could suggest that most of the users buy new devices, regardless of if they later discard or pass them over. To make our results more reliable, to estimate the shares between S -> S and S -> E choices we have obtained a single ratio across all eleven devices reported instead of assessing such probabilities for each device on its own. As a result, it has been estimated that consumers discard (used) electronics once again in 46% of the cases (25 out of 54 reports) instead of reusing them once again. This number was used in the TPL calculation for the corresponding transition probabilities and is different from the 42% mentioned in the manuscript (and the final Figure 3.4) as the latter is based on averages for five presented electronics categories only. All the data underlying such calculation is presented below.

## Appendix B: Underlying data spreadsheets

Complete survey-related results for all eleven product categories are in the spreadsheets below along with the results of the corresponding analysis presented in the manuscript:

<u>Results</u>:

| UNU code | Product | Reports collected | | | | | Possession spans | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Total | Type 0 (N -> EoL) | Type 1 (N -> S) | Type 2 (S -> S) | Type 3 (S -> EoL) | Type 0 (N -> EoL) | Type 1 (N -> S) | Type 2 (S -> S) | Type 3 (S -> EoL) |
| 204 | Vacuum cleaner | 4 | 1 | 1 | 1 | 0 | | | | |
| 302 | Desktop PC | 141 | 77 | 50 | 9 | 5 | 7.6 | 6.0 | 4.8 | 6.2 |
| 303 | Laptop computer | 132 | 72 | 44 | 8 | 8 | 6.1 | 4.6 | 2.8 | 2.6 |
| 304 | Printers (incl. scanners, multifunctionals) | 94 | 55 | 34 | 0 | 5 | 5.4 | 4.0 | 0.0 | 5.9 |
| 306 | Mobile phones (incl. smartphones) | 102 | 64 | 33 | 1 | 4 | 3.7 | 2.9 | 1.0 | 2.5 |
| 308 | Monitor (Cathode Ray Tube) | 1 | 1 | 0 | 0 | 0 | | | | |
| 309 | Monitor (Flat Panel) | 2 | 3 | 0 | 0 | 0 | | | | |
| 404 | Video recorders (DVD, Blue Ray, etc) | 11 | 3 | 8 | 0 | 0 | | | | |
| 405 | Speakers | 8 | 4 | 2 | 1 | 1 | | | | |
| 406 | Digital cameras | 17 | 7 | 8 | 2 | 0 | | | | |
| 407 | TV (CRT) | 6 | 4 | 2 | 0 | 0 | | | | |
| 408 | TV (Flat Panel Display) | 78 | 40 | 29 | 7 | 2 | 7.0 | 6.1 | 3.4 | 2.6 |

Analysis:

**Product lifetimes**

| UNU code | Product | TPL | Total lifespan (UNU) | Extension | Share of New -> SH | Share of SH -> EoL | Owners |
|---|---|---|---|---|---|---|---|
| 302 | Desktop PC | 11.6 | 9.2 | 53% | 39% | 36% | 1.9 |
| 303 | Laptop computer | 7.7 | 7.8 | 26% | 38% | 50% | 1.8 |
| 304 | Printers (incl. scanners, et | 7.1 | 7.6 | 31% | 38% | 100% | 1.4 |
| 306 | Mobile phones (smartpho | 4.7 | 5.1 | 27% | 34% | 80% | 1.7 |
| 408 | TV (Flat Panel Display) | 9.4 | 9.7 | 34% | 42% | 22% | 1.9 |
| | Averages: | | | 34% | 38% | 58% | 1.7 |

**Product durability and EoL**

| UNU code | Product | TUFF (adjusted) | Failed | Major failure | User caused | Not recycled |
|---|---|---|---|---|---|---|
| 302 | Desktop PC | 6.5 | 70% | 61% | 7% | 34% |
| 303 | Laptop computer | 4.9 | 88% | 81% | 13% | 28% |
| 304 | Printers (incl. scanners, et | 4.9 | 69% | 71% | 5% | 51% |
| 306 | Mobile phones (smartpho | 3.1 | 72% | 65% | 36% | 50% |
| 408 | TV (Flat Panel Display) | 6.5 | 82% | 76% | 9% | 30% |
| | Averages: | | 76% | 71% | 14% | 39% |

**Product hibernation**

| UNU code | Product | Hibernation time | Based on reports | Hibernating share | Condition: New | Condition: Used (functional) | Condition: Used, minor malfunction | Condition: Used, major malfunction | Major failure |
|---|---|---|---|---|---|---|---|---|---|
| 302 | Desktop PC | 1.4 | 129 | 70% | 1 | 8 | 21 | 14 | 32% |
| 303 | Laptop computer | 1 | 124 | 68% | 0 | 2 | 57 | 41 | 41% |
| 304 | Printers (incl. scanners, etc) | 1.2 | 93 | 73% | 0 | 1 | 13 | 14 | 50% |
| 306 | Mobile phones (smartphones) | 0.9 | 114 | 65% | 0 | 4 | 14 | 14 | 44% |
| 408 | TV (Flat Panel Display) | 0.4 | 72 | 51% | 0 | 0 | 2 | 1 | 33% |

**Reports analyzed**

| Report type | Amount |
|---|---|
| New -> EoL (Type 0) | 330 |
| New -> SH (Type 1) | 214 |
| SH -> SH (Type 2) | 29 |
| SH - EoL (Type 3) | 25 |
| Not in use | 392 |
| New -> Other | 28 |
| New -> Return | 16 |
| Used -> Other | 2 |
| Used -> Return | 1 |
| Total reports analyzed | 1037 |

# Related to Chapter 4

## Step 1: Market-level stock and flow modeling

The basis of our proposed model is the Markov chain described in the existing study (Amatuni et al., 2023). We depict its adaptation for our purposes in Figure S1.

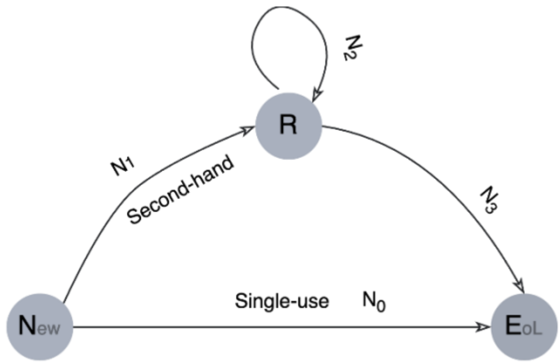


**Figure S1** Markov chain describing the stochastic model of product service life cycle, adapted from Amatuni et al. (2023)

Four user types were identified depending on their consumption pattern and interaction with the second-hand market. They are labeled as N0 through N3 in this work as described in Table S1.

| User type | Description of consumption pattern |
|---|---|
| $N_0$ | Linear use: Acquire new, use, dispose |
| $N_1$ | First use: Acquire new, use, resell |
| $N_2$ | Interim use: Acquire used, use, resell |
| $N_3$ | Last use: Acquire used, use, dispose |

**Table S1** Categorization and description of four identified user types

Within each user group, an average product possession lifespan has been estimated in the original study ($LT_i$) along with an average hibernation time $H$ for users from various countries. In this study, around 80% of respondents were from USA. Only user types N0 and N1 consume new products. With $N_i$ we simultaneously denote group sizes of the corresponding user types. Based on this framework, we consider the smartphone market from a stock and flow perspective. Stocks are four user groups of the corresponding sizes and use and ownership time spans. The yearly material outflows from the stocks adhere to the mass balance assumption and are equal to $f_i = \frac{N_i}{LT_i}$. Products' transition probabilities between three states (see Figure S1) were

recalculated based on such flows $f_i$ rather than the corresponding user group sizes $N_i$ as it was in the original study.
The manufacturing rate $M$ within a given time period $T$ in a market with population $P$ (sum of N0 through N3) can therefore be expressed as:

$$M = \frac{T * N_0}{LT_0} + \frac{T * N_1}{LT_1}$$

The resulting yearly average per-capita material (unit) requirement of smartphone consumption can be expressed as: $M/P/T$.

Step 2: Product lifetimes and user group sizes (collecting existing data)

The expected time between the very first purchase and the end-of-life (EoL) treatment or the expected total product lifetime (TPL) of each manufactured phone has been estimated in accordance with the stochastic framework from the original study.

The average product use time that, in contrast to ownership-based TPL, does not include the average hibernation period $H$ can be expressed as:

$$TPU = TPL - H$$

To estimate the effect of the reuse market on the output variables M, TPL, and TPU, the stock and flow model was run using different input values (see Step 5) for the two scenarios, as described in Table S2.

| Scenario | Description |
|---|---|
| Scenario A | Scenario based on consumer surveys data to approximate the current market situation |
| Scenario B | Alternative benchmark scenario in which no second-hand market exists |

**Table S2** Description of two scenarios for comparison of impact on manufacturing rate, total product lifetime and environmental impact

Scenario A is based on user-reported data collected via the existing open consumer survey (Amatuni et al., 2023). Average product possession times for each user segment and the ratios between consumer group sizes ($\frac{N_o}{N_1}$and $\frac{N_2}{N_3}$) were first based on the number of corresponding reports in the original survey (102 respondents).

Step 3: User group sizes and storage time (collecting new data)

Given limited data availability on the previous step for consumers who are reusing existing devices, an additional 108 consumer reports through the paid Amazon Mechanical Turk (MTurk) service were collected. In particular, we have collected more detailed data for second-hand product lifetimes and hibernation times (user groups $N_2$ and $N_3$). We additionally surveyed and accounted for devices that have been refurbished by the end of their reuse (assuming a 50% refurbishment rate by operators) and obtained a more accurate ratio between the corresponding groups sizes $\frac{N_2}{N_3}$. We also surveyed the direct rebound effect (shorted use time factor) for the group $N_2$ in case if they would need to purchase new devices instead.

Step 4: Direct rebound effect (integrating existing product use time change data)

As has been shown by previous studies, assuming no behavioural change and rebound effects caused by the possibility of participating in the second-hand market can be misleading. Hence, it would not be correct to assume that in scenario B, all users would use devices for the same length. Yet, no primary data can be collected for the fictitious scenario B in which no second-hand market exists. To estimate user behaviour in this scenario, insights on the effects of a hypothetical absence of a second-hand market reported in existing reports (Matsumoto et al., 2023) were utilized to 'convert' user types N1, N2, and N3 into N0. Accordingly, user type N1 would use their phones longer by 33 % if re-selling was not possible. User type N3 would use a new phone longer by 62 % if buying a used phone was not possible. To estimate such rebound effect for the user group N2 (both, buying and re-selling is not possible), we used new data from our additional survey (see Step 3), resulting in 114% longer use. These factors were applied to $LT_1$, $LT_2$ and $LT_3$ to estimate $LT_i{}'$ in the absence of a second-hand market. Values $LT_1{}'$, $LT_2{}'$, and $LT_3{}'$ were combined with the original $LT_0$ to estimate the modified $LT_0{}'$ in the market where everyone practices single-use behaviour.

Step 5: Estimating the required manufacturing rates for two scenarios

Given these data inputs and the mass balance equations from the stock and flow model, the resulting user group sizes, the magnitudes of flows between them, and the required rate of new product manufacturing were obtained for each scenario separately.

First, we defined the existing market setting using a stock and flow model (Scenario A). Table S3 reports the originally estimated smartphone use times by each user type (see Step 3) and the relative consumer group sizes resulting from model balancing.

| **User types** | **Relative user type occurrence (P=1)** | **Lifetime types** | **Average use time [years]** |
|---|---|---|---|
| $N_0$ | 0.38 | $LT_0$ | 2.5 |
| $N_1$ | 0.20 | $LT_1$ | 2.0 |
| $N_2$ | 0.23 | $LT_2$ | 1.6 |
| $N_3$ | 0.19 | $LT_3$ | 1.9 |
| M | 25 units/year per 100 users | | |

**Table S3** Input parameters for scenario A (actual scenario with second-hand market)

Similarly, Table S4 reports the resulting values for the user group sizes, average use times (considering reported behavioural change, see Step 4) and the required manufacturing rate in case of the absence of reuse (Scenario B).

| **User types** | **Relative user type occurrence** | **Lifetime types** | **Average use time [years]** |
|---|---|---|---|
| $N_0$ | 1 | $LT_0'$ | 2.9 |
| $N_1$ | 0 | $LT_1'$ | 2.7 |
| $N_2$ | 0 | $LT_2'$ | 3.4 |
| $N_3$ | 0 | $LT_3'$ | 3.1 |
| M | 34 units/year per 100 users | | |

**Table S4** Input parameters for scenario B (benchmark scenario where the second-hand market would not exist)

Step 6: Estimating the environmental impact of reuse

Here, the environmental impact related to the consumption of smartphones is calculated by multiplication of the resulting total manufacturing rate (see Step 5) of new smartphones $M$ with the global warming potential (GWP) factor $G$ related to the non-operational life cycle stages of a single smartphone:

$$E = M * G \quad (3)$$

Operational impacts arising from smartphone use, i.e. emissions from provisioning of electricity for battery charging, are not included, assuming that the total population-wide use time is identical in both scenarios and that increases in power efficiency with newer smartphones are negligible.

The value for $G$ is derived from existing research (Pamminger et al., 2021) that estimated the non-operational life cycle GWP of a smartphone to be 34.6 kg CO2e and the environmental expenditures of refurbishing a smartphone to be 3.41 kg CO2e.

No data on the share of smartphones that undergo treatment (repair, refurbishment) in between possession spans by users was identified in the literature. Instead, this data was estimated from a user survey. Of user type N2 responding to our survey, 22% stated to have purchased their phone in refurbished condition (78% in used condition), and 17% stated to have their device traded in or sold off to a business, such as a refurbishment operator, manufacturer, or retailer after their possession span ended (83% given away, sold to another person, donated). Therefore, from 24 annual second-hand phone transactions between per 100 users, 4.6 involve a refurbishment, and the remaining 19.4 are transactions without refurbishment. Transactions with refurbishment account for the above-cited environmental impact of refurbishment. Transactions without refurbishment only account for shipping expenditures (0.1 kg CO2e for a 2 kg parcel shipped on land for a 1000 km distance). Transaction impacts of phones that are not refurbished are considered negligible.

## References


Amatuni, L., Yamamoto, T., Baldé, C. P., Clemm, C., & Mogollón, J. M. (2023). Quantifying total lifetimes of consumer products: Stochastic modelling accounting for second-hand use and establishing an open-collaborative database. Resources, Conservation and Recycling, 197, 107103. https://doi.org/10.1016/j.resconrec.2023.107103

Matsumoto, M., Clemm, C., Awazu H, & Tominaga, J. (2023, May). Mobile phone reuse businesses in Japan and an estimation of their environmental load reduction effects. Vienna: Going Green - CARE INNOVATION.

Pamminger, R., Glaser, S., & Wimmer, W. (2021). Modelling of different circular end-of-use scenarios for smartphones. International Journal of Life Cycle Assessment, 26(3), 470–482. https://doi.org/10.1007/s11367-021-01869-2

# Related to Chapter 5

## SI1: Example matrices

Here, we present what the proposed model delivers while estimating the MC of copper and plastic for the simplified laptop manufacturing supply chain from the manuscript (see Figure 5.2 of the manuscript).

Calculating the regular supply array and the inventory vectors and comparing them to the incorporated supply and inventory vectors (see sub-section below for details) results in Table S1.

| Elementary flow | MC ($\tilde{\boldsymbol{g}}$) | NIMF (Δ) | MF ($\boldsymbol{g}$) |
|---|---|---|---|
| **Copper (extracted)** | 0.295 | 0.365 | 0.660 |
| **Crude oil** | 0.5 | 1 | 1.5 |
| **Copper (emitted)** | 0.030 | 0.030 | 0.060 |
| **Oil (emitted)** | 0.125 | 0.175 | 0.300 |
| Intermediate output | MC ($\tilde{\boldsymbol{t}}$) | NIMF (Δ) | MF ($\boldsymbol{t}$) |
| **Copper (raw)** | 0.295 | 0.365 | 0.660 |
| **Copper (refined)** | 0.295 | 0.305 | 0.600 |
| **Circuit board** | 1 | 0 | 1 |
| **Laptop** | 1 | 0 | 1 |
| **Oil** | 0.5 | 0.7 | 1.2 |
| **Electricity** | 0 | 1 | 1 |
| **Factory** | 0 | 0.001 | 0.001 |
| **Petrochemicals** | 1 | 1 | 2 |
| **Plastic** | 1 | 1 | 2 |

**Table S1** Material Composition (MC), Material Footprint (MF), and their difference as Non-Incorporated Material Footprint (NIMF) estimates for the elementary and intermediate flows from the simplified laptop example in kg. Based on the (original and modified) inventory ($\boldsymbol{g}$) and supply ($\boldsymbol{t}$) vectors obtained through the application of the proposed method. Notice, that a) the MC reported under $\tilde{\boldsymbol{t}}$ is prone to double counting and is not supposed to be summed up without accounting for it; b) not all of the materials enter the final product in their original form (0.5 bbl/barrel of oil versus 1 kg of plastic)

It can be seen that both the supply and the inventory vectors suggest 660 g of raw (extracted) copper as the MF while the modified vectors properly reduce this value to 295 g for the MC of the copper in the laptop. The inventory vector g additionally shows that 60 g of copper was emitted back into the environment. The total MF of crude oil extraction for laptop manufacturing is 1.5 bbl while 0.3 bbl dissipated (emitted). Notice, that the total MF of the oil is better estimated using the inventory vector $g$ as it accounts for the corresponding dissipation into the environment. While the modified inventory and supply vectors could suggest that 0.5 bbl of that oil was incorporated in the laptop, it could be more meaningful to consider the plastic content in the laptop instead: 1 kg of the incorporated plastic as the MC (see $\tilde{t}$) versus 2 kg of the total plastic footprint (see $t$). See Section SI8-D below which elaborates on these aspects.

Detailed calculations

The calculation starts with defining matrices and vectors: $A$, $P_A$, $P_B$, $B$, $f_k$ based on the observed supply chain (see Sheet 5 in the end of this chapter's supplementary), where the columns of all the matrices and vectors relate correspondingly to the mono-functional processes, the rows of the matrices $A$ and $P_A$ relate to the corresponding reference products of these processes, and the rows of the matrices $B$ and $P_B$ relate to the corresponding elementary flows.

There are four parameters in the matrix $P_A$ that are lower than zero: the non-incorporated fabric into the laptop, electricity into the fabric, and two partially incorporated inputs. For each 1.1 kg of the raw copper used only around 90% is embodied into the refined 1 kg of copper (the rest is emitted as dissipative losses, see matrix $B$), and additionally, 2.5% of the refined copper becomes scrap during laptop manufacturing.

Matrix $P_B$ describes the one fifth non-incorporated flow of extracted crude oil that is dissipated back to the environment (see matrix $B$ as well). The rest of the environmental flows along the supply chain are incorporated.

It is important to notice that some of the values in the filtering matrices ($P_A$ and $P_B$) can be derived and even have to be in line with the corresponding losses described in the technosphere or the biosphere matrix. For example, the incorporation parameter for the raw copper entering the refining process is set to around 0.91 as the technosphere reports 0.1 kg out of 1.1 kg being dissipated in the process.

The resulting modified technosphere and biosphere matrices are presented under Sheet 5 in in the end of this chapter's supplementary.

The same calculation could be derived using Activity Browser as it can be used to replicate a trial LCI database based on Figure 5.2 of the main manuscript. Indeed, such observation of the trial supply chain in the Activity

Browser, using both objects (inventory vector and supply arrays), resulted in 660 g of copper MF for the production of a single laptop.

SI2: Double-counting example

In the following example (all flows are incorporated and zero losses are

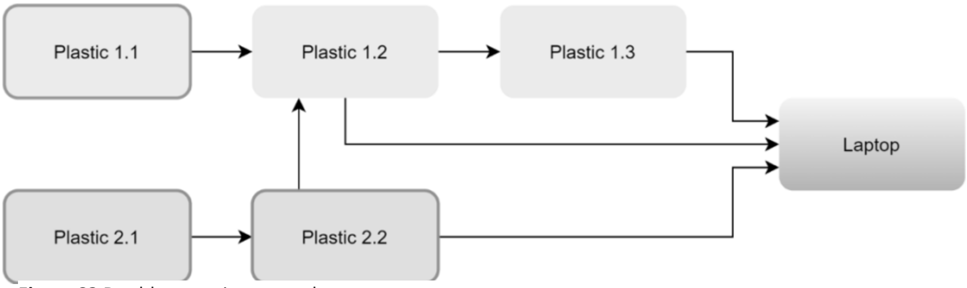


**Figure S2** Double-counting example

assumed), two distinct types of plastic (Plastic 1 and 2) are used to manufacture a Laptop (see Figure S1).
Two finished forms (Plastic 1.3 and 2.2) are used to produce the Laptop along with a more raw Plastic 1.1 input. The supply array will contain positive values for all five plastic types. It could be seen that to obtain the total content of the material Plastic 1 in the laptop, only one of its three consecutive forms has to be selected from the supply array to avoid double counting. For Plastic 1, there is an additional mass of the earlier form Plastic 1.2 which is used directly in the Laptop and will be missed if we would select Plastic 1.3. Hence, Plastic 1.1 or Plastic 1.2 has to be selected from the supply array as the *source activity* for Plastic 1 content estimation. The same logic applies when estimating the Plastic 2 material content. Only one activity has to be selected out of two forms, and it does not matter which one, Plastic 2.1 or Plastic 2.2. The MSF $\mu_m$ that sums up only such appropriate values has been introduced in the Mathematical model section of the manuscript.

Moreover, if one is interested in the estimation of the total plastic content in the Laptop rather than the specific plastic materials, the masses of the two plastics have to be summed up. However, if the final forms are selected (1.2 and 2.2), the Plastic 1.2 material flow will contain some of the required Plastic 2.2 already. Hence, we should step back to the previous form of Plastic 1 and consider the mass of Plastic 1.1 instead. Hence, selecting Plastic 1.1 activity as a source activity for the first plastic type and Plastic 2.2 as a source activity for the second plastic type in the material selection factions will allow adding their inputs from the supply array without double counting both when estimating the individual material contents as well as the aggregated sums.

We call such a resulting bill of the source activities from the LCI database as the *material dictionary*. In practice, it lists the set of synthetic materials of interest and the corresponding material forms (activities in the LCI database), therefore, defining the MSFs. These could be grouped together when desired to estimate more aggregate material content (see Mathematical model section of the manuscript).

It could appear as if selecting the earliest forms for each synthetic material would allow us to avoid any of the above-mentioned challenges. Nevertheless, that will quickly move the practitioner far from the initial material of interest and will strongly complicate the comprehensibility of the resulting MC of products (imagine sand, soda ash, and limestone contents reported instead of glass content).

Hence, manual work of selecting the source activities would be needed for each synthetic material. The general approach suggested here is as follows: for each synthetic material of interest, select the latest possible form (activity in the LCI database), so that 1) the selected activity does not have a link (possibly indirect) with any of the other source activities 2) none of the earlier forms for that material have parallel links (possibly indirect) to the final product.

It has to be noted that double-counting becomes an issue only when one is willing to sum the material flows from different inputs, for example, for the total plastic content in the Laptop (see Figure S1 above). The incorporated masses of Plastic 1.3 or Plastic 2.2 on their own will be still accurate.

Additionally, here, we assumed that the considered materials appear rather later in the economy's supply chain and do not involve any chemical transformations anymore. That is similar to natural materials (i.e. metals) that are stable along the supply chain allowing to reasonably estimate their content in the reference products at the end of the chain. Otherwise, Plastic 1.1 material in the final product could be of a completely different nature than Plastic 1.1 material from its original supplying activity, and its content would not make much sense to measure (think of the limestone example above).

## SI3: Material dictionary for plastics in Ecoinvent 3.6

To be able to estimate the total plastic content in the products of interest, first, a comprehensive list of plastics has been obtained (see Table S2).

| **Name** | **Symbol** |
|---|---|
| polyamide | PA |
| polycarbonate | PC |
| polyester | PES |
| polyethylene | PE |
| polyethylene terephthalate | PET |
| polypropylene | PP |
| polystyrene | PS |
| polyurethane | PUR |
| polyol | PU:polyol |
| phenyl isocyanate | PU:phenyl isocyanate |
| polyvinylchloride | PVC |
| poly vinyl chloride | PVC |
| polyvinylidenchloride | PVDC |
| acrylonitrile-butadiene-styrene | ABS |
| epoxy | EPOXY |
| polymethyl methacrylate | PMMA |
| phenolic resin | PF |
| polyvinylfluoride | PVF |
| melamine formaldehyde | MF |
| urea formaldehyde | UF |
| polylactide | PLA |
| polysulfone | PSU |
| styrene-acrylonitrile | SAN |
| acrylic | ACRYLIC |
| bisphenol A epoxy based vinyl ester resin | VER |
| ethylene-vinyl acetate | EVA |
| ethylvinylacetate | EVA |
| polymer foaming | FOAM |
| polyphenylene sulfide | PPS |

**Table S2** List of plastics considered in the study

For each plastic name, all the activities in ecoinvent 3.6 have been scanned for the matching names (see /dict_gen/mat_dict_gen.py under the GitHub page). That allowed to link each plastic type with the corresponding producing activities in ecoinvent. Additionally, PE and PET plastics have the same keyword under their names, hence, a separate correction was required for such.

It was assumed that all of the ecoinvent activities linked to the same plastic type do not have a duplicate mass between them (see SI2).

The resulting list of activities has been imported into the main script for the different (and the total) plastics content in the products of interest. See Sheet 3 in the end of this chapter's supplementary for detailed results of plastic content in a laptop.

This approach of automatic scanning of ecoinvent activities' names for the matching keywords with the material names, in theory, could be applied to any type of material while saving such in the input files (see GitHub page).

## SI4: Calculations for the case study

See Sheet 1 in the end of this chapter's supplementary for the calculations related to the case study. In particular, for each of the three products and materials resulting material content values are presented against the average of two theoretical values from the existing sources (the sources are cited in the same document). Tantalum content in a conventional passenger vehicle has been found in only one existing source.

Such values are calculated for two possible vectors (elementary and intermediate flows) and for three existing ecoinvent system models. All the values describe the relative (to the product's total weight) material content, hence the total weights of the explored products were needed. For the experimental values, these were taken from the corresponding ecoinvent production activities' descriptions. For the theoretical values, alternative sources were used for weight estimates.

Next, relative and absolute errors are calculated between our experimental and the existing theoretical values. Finally, the results were averaged across products and materials. This allowed observing how two different approaches performed 'on average' using different databases and to point out the most accurate combinations of such.

## SI5: Results for plastics in the case study

To exemplify, here, we present the detailed plastics content for the laptop obtained by applying the supply array approach on the consequential model of ecoinvent (see Sheet 4 in the end of this chapter's supplementary).

## SI6: Defining the avoid list

It is important to acknowledge 1) the sensitivity of the keywords-based scanning to a specific product and materials of interest and 2) the need for its manual adjustment each time new materials are explored.

We argue that, given the types of products explored in our case study (consumer products that appear rather later in the material supply chains), the size of the avoid list appeared to be comprehensive enough for an accurate MC estimation. Even though the keywords from the avoid list we used did not focus on distinguishing non-incorporated chemical compounds earlier in the material supply chains, since in the end they often become embodied in much bigger non-incorporated materials and components (covered by the keywords like 'infrastructure', 'packaging', etc.), such earlier forms of materials still end up being filtered out by our algorithm through avoidance of their later bulkier forms.

It is undoubtful that extending the avoid list with a more detailed list of keywords is supposed to deliver more accurate results, yet, for the specific type of consumer products we have selected, our results appear to converge with more keywords. To define the list itself, we would repeatedly revisit ecoinvent activities searching for reappearing keywords closer to the final consumer products of interest and adding them to the list. We have noticed that further from the final product we search for non-incorporated keywords to avoid, less impact such keywords have on the resulting MC estimate. Yet, if the algorithm is applied to estimate the MC of other products, especially closer to the primary products in the material supply chains, the avoid list will need to be redefined, making it a time-consuming task in itself.

## SI7: Defining material selection, conversion, and aggregation

When the supply array is used for MC estimation, the practitioner needs to pay attention to the selection of materials from the supply array to avoid potential double-counting of mass (see Section SI2). Further, values in $\tilde{g}$ and $\tilde{t}$ are typically expressed in a range of units (e.g. mass, volume, energy). Thus, if the practitioner is interested in MC expressed in weight, an additional conversion step is necessary.

Hence, to obtain the content (total weight) of the material $m$ in the product $k$ ($w_{k_m}$), it is required to select, or sometimes to sum up, and convert the material flows from either $\tilde{g}$ or $\tilde{t}$ that are related to the same material of interest (e.g. copper extraction from different types of ores resulting in several copper-containing flows in the inventory vector):

$$w_{k_m} = \mu_m(\tilde{t})$$

where we call $\mu_m$ the *material selection function.* The MC of the material *m* in the product $k$ can be defined, then, as $w_{k_m}$. In the Results section of the main manuscript, we considered the relative MC as a ratio $\frac{w_{km}}{w_k} * 100\%$ where $w_k$ is the total weight of the product.

Sometimes, estimates for more aggregate materials are of the practitioner's interest (e.g. plastics instead of PET and PVC). In this case, the material selection functions of the detailed materials have to be grouped (summed up) forming the *material aggregation function*.

## SI8-A: Software and LCI database preparation

There are various products in the market, and for this study, we have used the Activity Browser (Steubing et al., 2020), a graphical user interface to the brightway LCA framework (Mutel, 2017). The Activity Browser allows to either organize new LCI databases (supply chains) or to work with the existing ones such as ecoinvent. Given a specific final demand vector (*reference flows* in Activity Browser), its functionality allows exploring the inventory vector and the supply array *(biosphere and technosphere flows* in Activity Browser). Simultaneously, Brightway enables the execution of diverse LCI computations and allows the exploration of identical objects through a more flexible, coding-oriented approach.

Apart from the filtering matrices $P$ and the material selection function $\mu_m$, all the vectors, matrices, and functions involved in the proposed model will be available to a practitioner given access to one of the existing LCI databases and the related computation framework.

SI8-B: Manual determination of the material incorporation

For simplicity, in this study, it will be assumed that any material extracted from the biosphere is completely incorporated in the output of the corresponding extracting activities, in other words, we assume no losses during raw material extraction. This allows us to restrict our application to the $P_A$ matrix only (denoted simply as $P$ from now on) as the $P_B$ matrix (material filtering for the elementary flows) becomes matrix of ones and does not impact the calculations

To allow manual filtering and distinguishing of the incorporated versus non-incorporated material flows (determining filtering matrix $P$), a modified version of the open-source LCA software Activity Browser has been developed allowing the user to assign an additional 'Incorporated' parameter (values between 0 and 1) to any of the intermediate exchanges within the LCI dataset of application.

Next, in brightway, all values in the technosphere matrix related to the LCI database are multiplied by the corresponding 'Incorporated' parameter sourced from the Activity Browser interface so that the modified matrix $\tilde{A}$ is obtained.

SI8-C: Algorithmic determination of the material incorporation

Manual application of the 'Incorporated' parameter for the exchanges in the Activity Browser seems to be manageable for relatively short supply chains and small LCI databases such as the exemplifying laptop toy model. For practical purposes, as LCI databases are typically more comprehensive, we propose an automatic filtering algorithm for a general LCI database. It is later applied to the ecoinvent database for our case study.

The filtering algorithm scans the whole LCI database for all the activities and all the exchanges and it automatically assigns the value of zero (0) to the corresponding 'Incorporated' parameter if the exchange's name (process input or output) contains any keyword from the previously prepared *avoid list.* Such avoid list of keywords describes common auxiliary or any other non-incorporated flows within the LCI database and is highly dependent on a specific database of the application. However, several common categories of non-incorporated inputs can be identified: packaging, transportation, energy, buildings, machinery, infrastructure, and water (unless interested in water content). Additionally, some of the LCI databases like ecoinvent list outputs as negative inputs (including the waste and used product treatment) which then have to be automatically filtered.

Yet, in its currently implemented form, the algorithmic parameter assignment is not capable of separating incorporated material inputs from their respective losses and is rather binary (0 or 1). This, however, could be improved allowing the algorithm to assign losses-related incorporation parameters between 0 and 1 to the material flows on a per-material or per-activity basis. This will require separate quantitative research on various types of losses (process or dissipative) and will result in a rather manual character of the resulting algorithm. Since such losses are expected to be relatively minor, we leave this improvement for future work.

### SI8-D: Implementing material selection and aggregation

A manual definition of the material selection functions will be required if the supply array is used for MC estimation. Sometimes, existing *material depletion assessment methods*, for instance, EDIP (Klinglmair et al., 2014), can be used for a limited number of materials (especially metals) as for the material selection function in our method to sum up the related flows in the inventory vector. This can be handy if, for instance, the metal is extracted from various sources and appears under several values in the resulting inventory.

At the step of material selection and aggregation, two different challenges are tackled.

The approach using the supply array is prone to double counting. This is caused by the fact that the technosphere-originating materials have intertwined and interdependent supply chains upstream where the same material mass could be present in several consecutive forms, products, and activities. For instance, when calculating the total iron content in a vehicle, either the iron flow or the steel flow (which inputs iron) has to be included, even though both flows carry iron and both will be present in the supply array of the vehicle. Hence, the material selection process has to account for such possibilities. This does not happen with the estimation using the inventory vector, however, since the elementary flows are the very first in the whole supply chain and do not have any predecessors with a redundant mass. See SI2 for a detailed discussion of this challenge.

Additionally, if several materials (e.g. PET and PVC) relate to the same material group (plastic), material aggregation can be performed to sum their masses up (see Section SI7).

To approach both points above, a *material dictionary* has been used in the code that for each material of practitioner's interest lists the keys of the corresponding activities in the LCI database that represent that material and that are intended to be summed up during later calculations. In practice, the material dictionary defines the analytical material selection and aggregation functions for estimating the MC (see Section SI7). A certain understanding of the supply chains and the flow names is required to make meaningful choices at this step.

## References


Klinglmair, M., Sala, S., & Brandão, M. (2014). Assessing resource depletion in LCA: A review of methods and methodological issues. International Journal of Life Cycle Assessment, 19(3), 580–592. https://doi.org/10.1007/s11367-013-0650-9

Mutel, C. (2017). Brightway: An open source framework for Life Cycle Assessment. The Journal of Open Source Software. https://doi.org/10.21105/joss.00236

Steubing, B., de Koning, D., Haas, A., & Mutel, C. L. (2020). The Activity Browser — An open source LCA software building on top of the brightway framework. Software Impacts. https://doi.org/10.1016/j.simpa.2019.100012

Sheet 1 (data analysis):

| DESCRIPTION | | Passenger car (1 kg) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Bioflows | | | Technoflows | | | *Prev. studies* | | |
| | | cutoff36 | apos36 | conseq36 | cutoff36 | apos36 | conseq36 | *MC 1* | *MC 2* | *Average* |
| Copper | composition | 1.18% | 0.73% | 1.00% | 0.94% | 0.47% | 0.96% | 1.80% | 1.80% | *1.80%* |
| | intensity | | | 1.69% | | | 1.52% | | | |
| Aluminium | composition | 5.18% | 2.71% | 18.20% | 16.63% | 13% | 14.83% | 9% | 10% | *9.50%* |
| | intensity | | | 20.77% | | | 16.90% | | | |
| Tantalum | composition | 0.008% | 0.008% | 0.008% | 0.005% | 0.005% | 0.005% | 0.004% | | *0.004%* |
| | intensity | | | 0.00821% | | | 0.005% | | | |
| Plastic | composition | | | | 15.00% | 14.60% | 15.01% | 18.5% | *13.50%* | *16.00%* |
| | intensity | | | | | | 20.00% | | | |
| Other | | | | | | 71.63% | 69.20% | | | 72.70% |
| | | | | | | | | | | |
| | | 34% | 59% | 44% | 48% | 74% | 47% | | | |
| | | | | | | | | | | |
| | | 45% | 71% | 92% | 75% | 40% | 56% | | | |
| | Relative error | | | | | | | | | |
| | | 105% | 101% | 105% | 17% | 14% | 17% | | | |
| | | | | | | | | | | |
| | | - | - | - | 6% | 9% | 6% | | | |
| | | | | | | | | | | |
| | Averaged per method/prod/db (metals) | 62% | 77% | 80% | 46% | 43% | 40% | | | |
| | Averaged per method/prod/db | | | | 36% | 34% | 31% | | | |
| | | | | | | | | | | |
| | Averaged per method/db (metals) | **50.50%** | **49.67%** | **64.14%** | **40.69%** | **35.87%** | **32.85%** | | | |
| | Averaged per method/db (plastic) | | | | **5.71%** | **6.57%** | **5.73%** | | | |
| | Averaged per method/db | | | | 32% | 29% | 26% | | | |
| | | | | | | | | | | |
| | | 0.62% | 1.07% | 0.80% | 0.86% | 1.33% | 0.84% | | | |
| | | | | | | | | | | |
| | | 4.32% | 6.79% | 8.70% | 7.13% | 3.80% | 5.33% | | | |
| | Absolute error | | | | | | | | | |
| | | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | | | |
| | | | | | | | | | | |
| | | - | - | - | 1.00% | 1.40% | 0.99% | | | |
| | | | | | | | | | | |
| | Averaged per method/prod/db (metals) | 1.65% | 2.62% | 3.17% | 2.66% | 1.71% | 2.06% | | | |
| | | | | | | | | | | |
| | Averaged per method/db (metals) | **1.62%** | **1.81%** | **2.21%** | **1.47%** | **1.27%** | **0.97%** | | | |
| | Averaged per method/db (plastic) | | | | **1.56%** | **1.70%** | **1.57%** | | | |
| | Averaged per method/prod/db | | | | 2% | 2% | 2% | | | |
| | Averaged per method/db | | | | 1.5% | 1.4% | 1.1% | | | |

| DESCRIPTION | | Laptop (3.15 kg) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Bioflows | | | Technoflows | | | *Prev. studies* | | |
| | | cutoff36 | apos36 | conseq36 | cutoff36 | apos36 | conseq36 | *MC 1* | *MC 2* | *Average* |
| Copper | composition | 8.56% | 7.71% | 10.03% | 9.09% | 8.34% | 5.19% | 6.85% | 4.33% | *5.59%* |
| | intensity | | | 18.73% | | | 11.87% | | | |
| Aluminium | composition | 8.04% | 7.34% | 14.99% | 12.54% | 9.62% | 12.01% | 8.44% | 16.43% | *12.44%* |
| | intensity | | | 19.73% | | | 15.50% | | | |
| Tantalum | composition | 0.009% | 0.008% | 0.009% | 0.005% | 0.005% | 0.005% | 0.079% | 0.048% | *0.06%* |
| | intensity | | | 0.00881% | | | 0.00501% | | | |
| Plastic | composition | | | | 30.49% | 30.36% | 30.46% | 40.58% | 25.800% | *33.19%* |
| | intensity | | | | | | 61.62809% | | | |
| Other | | | | | | 51.68% | 52.34% | | | 48.72% |
| | | | | | | | | | | |
| | | 53% | 38% | 79% | 63% | 49% | 7% | | | |
| | | | | | | | | | | |
| | | 35% | 41% | 21% | 1% | 23% | 3% | | | |
| | Relative error | | | | | | | | | |
| | | 86% | 87% | 86% | 92% | 92% | 92% | | | |
| | | | | | | | | | | |
| | | - | - | - | 8% | 9% | 8% | | | |
| | | | | | | | | | | |
| | Averaged per method/prod/db (metals) | 58% | 55% | 62% | 52% | 55% | 34% | | | |
| | Averaged per method/prod/db | | | | 41% | 43% | 28% | | | |
| | | | | | | | | | | |
| | Averaged per method/db (metals) | | | | | | | | | |
| | Averaged per method/db (plastic) | | | | | | | | | |
| | Averaged per method/db | | | | | | | | | |
| | | | | | | | | | | |
| | | 2.97% | 2.12% | 4.44% | 3.50% | 2.75% | 0.40% | | | |
| | | | | | | | | | | |
| | | 4.40% | 5.10% | 2.56% | 0.11% | 2.82% | 0.43% | | | |
| | Absolute error | | | | | | | | | |
| | | 0.05% | 0.06% | 0.05% | 0.06% | 0.06% | 0.06% | | | |
| | | | | | | | | | | |
| | | - | - | - | 2.70% | 2.83% | 2.73% | | | |
| | | | | | | | | | | |
| | Averaged per method/prod/db (metals) | 2.47% | 2.42% | 2.35% | 1.22% | 1.87% | 0.30% | | | |
| | | | | | | | | | | |
| | Averaged per method/db (metals) | | | | | | | | | |
| | Averaged per method/db (plastic) | | | | | | | | | |
| | Averaged per method/prod/db | | | | 2% | 2% | 1% | | | |
| | Averaged per method/db | | | | | | | | | |

| DESCRIPTION | | Refrigerator (60 kg) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Bioflows | | | Technoflows | | | *Prev. studies* | | |
| | | cutoff | apos | conseq | cutoff | apos | conseq | *MC 1* | *MC 2* | *Average* |
| Copper | composition | 2.23% | 2.02% | 2.94% | 2.23% | 2.04% | 2.24% | 1.78% | 1.70% | *1.74%* |
| | intensity | | | 3.11% | | | 2.38% | | | |
| Aluminium | composition | 4.32% | 3.43% | 4.69% | 3.70% | 2.94% | 3.75% | 4.27% | 0.90% | *2.59%* |
| | intensity | | | 4.90% | | | 3.92% | | | |
| Tantalum | composition | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | *0.00%* |
| | intensity | | | 0.00002% | | | 0.00001% | | | |
| Plastic | composition | | | | 36.83% | 36.72% | 36.84% | 31.99% | 39.70% | *35.85%* |
| | intensity | | | | | | 58.87% | | | |
| Other | | | | | | 58.30% | 57.17% | | | 59.83% |
| | Relative error | 28% | 16% | 69% | 28% | 17% | 28% | | | |
| | | 67% | 33% | 81% | 43% | 14% | 45% | | | |
| | | 0% | 0% | 0% | 0% | 0% | 0% | | | |
| | | - | - | - | 3% | 2% | 3% | | | |
| | Averaged per method/prod/db (metals) | 32% | 16% | 50% | 24% | 10% | 25% | | | |
| | Averaged per method/prod/db | | | | 19% | 8% | 19% | | | |
| | Averaged per method/db (metals) | | | | | | | | | |
| | Averaged per method/db (plastic) | | | | | | | | | |
| | Averaged per method/db | | | | | | | | | |
| | Absolute error | 0.49% | 0.28% | 1.20% | 0.49% | 0.30% | 0.50% | | | |
| | | 1.74% | 0.85% | 2.11% | 1.12% | 0.36% | 1.17% | | | |
| | | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | | | |
| | | - | - | - | 0.98% | 0.87% | 0.99% | | | |
| | Averaged per method/prod/db (metals) | 0.74% | 0.38% | 1.10% | 0.54% | 0.22% | 0.55% | | | |
| | Averaged per method/db (metals) | | | | | | | | | |
| | Averaged per method/db (plastic) | | | | | | | | | |
| | Averaged per method/prod/db | | | | 1% | 0% | 1% | | | |
| | Averaged per method/db | | | | | | | | | |

| | | **Average error per material** | |
|---|---|---|---|
| | | Relative error | Absolute error |
| **Copper** | | 43.51% | 1.39% |
| **Aluminium** | | 43.71% | 3.27% |
| **Tantalum** | | 49.64% | 0.02% |
| **Plastic** | | 6.00% | 1.61% |

Sheet 2 (references for the theoretical product composition sources):

| # | Source |
|---|---|
| 1 | Transport relies on copper, from trains to planes to electric vehicles [WWW Document], 2018. [WWW Document]. European Copper Institute. URL https://copperalliance.org.uk/about-copper/applications/transportation/ (accessed 11.4.21). |
| 2 | Mock, P. (Ed.), 2016. European Vehicle Market Statistics [WWW Document]. URL https://theicct.org/sites/default/files/publications/ICCT_Pocketbook_2016.pdf (accessed 11.4.21). |
| 3 | Brahmst, E., 2006. Copper in end-of-life vehicle recycling [WWW Document]. URL https://www.cargroup.org/wp-content/uploads/2017/02/Copper-in-End_of_Life-Vehicle-Recycling.pdf (accessed 11.4.21). |
| 4 | Improving Sustainability in the Transport Sector Through Weight Reduction and the Application of Aluminium [WWW Document], n.d. [WWW Document]. URL https://transport.world-aluminium.org/fileadmin/_migrated/content_uploads/1274789871IAI_EAA_AA_TranspoSustainability_final.pdf (accessed 11.4.21). |
| 5 | European Aluminium Association. (2013). Aluminium in Cars–Unlocking the light-weighting potential. *European Aluminium Association, Brussels*. |
| 6 | Field III, F. R., Wallington, T. J., Everson, M., & Kirchain, R. E. (2017). Strategic materials in the automobile: a comprehensive assessment of strategic and minor metals use in passenger cars and light trucks. *Environmental science & technology*, *51*(24), 14436-14444. |
| 7 | Emilsson, E., & Dahllöf, L. (2019). Plastics in passenger cars-A comparison over types and time. |
| 8 | Szostak, M. A. R. E. K. (2011). Recycling of pp/epdm/talc car bumpers. *Chemicke Listy*, *105*(15), s307-s309. |
| 9 | Van Eygen, E., De Meester, S., Tran, H. P., & Dewulf, J. (2016). Resource savings by urban mining: The case of desktop and laptop computers in Belgium. *Resources, conservation and recycling*, *107*, 53-64. |
| 10 | Park, S., Jung, M., Kim, S., Han, S., Jung, I., Park, J., & Park, J. (2018). Evaluation of Recycling Resources in Discarded Information and Communication Technology Devices (Smartphones, Laptop computers). *Journal of the Korean Institute of Resources Recycling*, *27*(3), 16-29. |
| 11 | Oguchi, M., Murakami, S., Sakanakura, H., Kida, A., & Kameya, T. (2011). A preliminary categorization of end-of-life electrical and electronic equipment as secondary metal resources. *Waste management*, *31*(9-10), 2150-2160. |

| | |
|---|---|
| 12 | Ueberschaar, M., Dariusch Jalalpoor, D., Korf, N., & Rotter, V. S. (2017). Potentials and barriers for tantalum recovery from waste electric and electronic equipment. *Journal of Industrial Ecology*, *21*(3), 700-714. |
| 13 | Report on Life Cycle Inventory (LCI) Analyses of Refrigerators [WWW Document], 2014. [WWW Document]. The Japan Electrical Manufacturers' Association. URL https://www.jema-net.or.jp/English/businessfields/environment/data/report_lci.pdf (accessed 11.4.21). |
| 14 | Kim, K., Cho, H., Jeong, J., & Kim, S. (2014). Size, shape, composition and separation analysis of products from waste refrigerator recycling plants in South Korea. *Materials Transactions*, M2013306. |


Sheet 3 (laptop plastics):

| Plastic type | MC (kg/unit) | MC (%) |
|---|---|---|
| **ABS** | 0.016 | 0.50 |
| **ACRYLIC** | 0.016 | 0.50 |
| **EPOXY** | 0.048 | 1.52 |
| **EVA** | 0.000 | 0.00 |
| **FOAM** | 0.000 | 0.00 |
| **MF** | 0.000 | 0.00 |
| **PA** | 0.015 | 0.48 |
| **PC** | 0.063 | 1.98 |
| **PE** | 0.071 | 2.26 |
| **PES** | 0.166 | 5.27 |
| **PET** | 0.010 | 0.31 |
| **PF** | 0.013 | 0.42 |
| **PLA** | 0.000 | 0.00 |
| **PMMA** | 0.106 | 3.36 |
| **PP** | 0.001 | 0.02 |
| **PPS** | 0.000 | 0.01 |
| **PS** | 0.426 | 13.54 |
| **PSU** | 0.000 | 0.00 |
| **PU: phenyl isocyanate** | 0.000 | 0.00 |
| **PU: polyol** | 0.000 | 0.00 |
| **PUR** | 0.000 | 0.00 |
| **PVC** | 0.007 | 0.22 |
| **PVDC** | 0.000 | 0.00 |
| **PVF** | 0.002 | 0.07 |

| | | |
|---|---:|---:|
| **SAN** | 0.000 | 0.00 |
| **UF** | 0.000 | 0.00 |
| **Total** | **0.96** | **30.46** |

Sheet 4 (material composition over material footprint ratio):

| **Product / material** | **Cu** | **Al** | **Ta** | **Plastics** |
|---|---|---|---|---|
| **Passenger car** | 1.58 | 1.14 | 1.00 | 1.33 |
| **Laptop** | 2.29 | 1.29 | 1.00 | 2.02 |
| **Refrigerator** | 1.07 | 1.04 | | 1.60 |

Sheet 5 (matrices for the simple example):

| **A** | Cu extr | Cu ref | PCB | Laptop | Oil | Electr | Factory | Petrocher | Plastic |
|---|---:|---:|---:|---:|---:|---:|---:|---:|---:|
| Cu extr | 1 | -1.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cu ref | 0 | 1 | -0.1 | -0.2 | 0 | 0 | -300 | 0 | 0 |
| PCB | 0 | 0 | 1 | -1 | 0 | 0 | 0 | 0 | 0 |
| Laptop | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| Oil | 0 | 0 | 0 | 0 | 1.2 | -0.2 | 0 | -1 | 0 |
| Electr | 0 | 0 | 0 | 0 | 0 | 1 | -1000 | 0 | 0 |
| Factory | 0 | 0 | 0 | -0.001 | 0 | 0 | 1 | 0 | 0 |
| Petrochem | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | -1 |
| Plastic | 0 | 0 | 0 | -1 | 0 | 0 | -1000 | 0 | 1 |

| **B** | Cu extr | Cu ref | PCB | Laptop | Oil | Electr | Factory | Petrochem | Plastic |
|---|---:|---:|---:|---:|---:|---:|---:|---:|---:|
| Cu raw | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Crude oil | 0 | 0 | 0 | 0 | 1.5 | 0 | 0 | 0 | 0 |
| Cu emis. | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Oil emis. | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 |

| **P^A** | | | | | | | | | |
|---|---:|---:|---:|---:|---:|---:|---:|---:|---:|
| Cu extr | 1 | **0.9** | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Cu ref | 1 | 1 | 1 | **0.975** | 1 | 1 | 1 | 1 | 1 |
| PCB | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Laptop | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Oil | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Electr | 1 | 1 | 1 | 1 | 1 | 1 | **0** | 1 | 1 |
| Factory | 1 | 1 | 1 | **0** | 1 | 1 | 1 | 1 | 1 |
| Petrochem | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Plastic | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

| **P^B** | Cu extr | Cu ref | PCB | Laptop | Oil | Electr | Factory | Petrochem | Plastic |
|---|---:|---:|---:|---:|---:|---:|---:|---:|---:|
| Cu raw | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Crude oil | 1 | 1 | 1 | 1 | **0.80** | 1 | 1 | 1 | 1 |
| Cu emis. | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Oil emis. | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

| A ~ | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Cu extr | 1 | -1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cu ref | 0 | 1 | -0.1 | -0.195 | 0 | 0 | -300 | 0 | 0 |
| PCB | 0 | 0 | 1 | -1 | 0 | 0 | 0 | 0 | 0 |
| Laptop | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| Oil | 0 | 0 | 0 | 0 | 1.2 | -0.2 | 0 | -1 | 0 |
| Electr | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| Factory | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| Petrochem | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | -1 |
| Plastic | 0 | 0 | 0 | -1 | 0 | 0 | -1000 | 0 | 1 |

| A~-1 | Cu extr | Cu ref | PCB | Laptop | Oil | Electr | Factory | Petrocher | Plastic |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 1 | 0.1 | 0.295 | 0 | 0 | 300 | 0 | 0 |
| | 0 | 1 | 0.1 | 0.295 | 0 | 0 | 300 | 0 | 0 |
| | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| | 0 | 0 | 0 | 0.416667 | 0.833333 | 0.166667 | 416.6667 | 0.416667 | 0.416667 |
| | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| | 0 | 0 | 0 | 0.5 | 0 | 0 | 500 | 0.5 | 0.5 |
| | 0 | 0 | 0 | 1 | 0 | 0 | 1000 | 0 | 1 |

| B~ | Cu extr | Cu ref | PCB | Laptop | Oil | Electr | Factory | Petrocher | Plastic |
|---|---|---|---|---|---|---|---|---|---|
| Cu raw | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Crude oil | 0 | 0 | 0 | 0 | 1.2 | 0 | 0 | 0 | 0 |
| Cu emis. | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Oil emis. | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 |

| g~ | | | g | |
|---|---|---|---|---|
| Cu raw | **0.295** | | Cu raw | **0.660** |
| Crude oil | 0.500 | | Crude oil | 1.500 |
| Cu emis. | 0.030 | | Cu emis. | 0.060 |
| Oil emis. | 0.125 | | Oil emis. | 0.300 |

| A-1 | Cu extr | Cu ref | PCB | Laptop | Oil | Electr | Factory | Petrocher | Plastic | | fk |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 1.1 | 0.11 | 0.66 | 0 | 0 | 330 | 0 | 0 | | 0 |
| | 0 | 1 | 0.1 | 0.6 | 0 | 0 | 300 | 0 | 0 | | 0 |
| | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | | 0 |
| | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | | 1 |
| | 0 | 0 | 0 | 1 | 0.833333 | 0.166667 | 583.3333 | 0.416667 | 0.416667 | | 0 |
| | 0 | 0 | 0 | 1 | 0 | 1 | 1000 | 0 | 0 | | 0 |
| | 0 | 0 | 0 | 0.001 | 0 | 0 | 1 | 0 | 0 | | 0 |
| | 0 | 0 | 0 | 1 | 0 | 0 | 500 | 0.5 | 0.5 | | 0 |
| | 0 | 0 | 0 | 2 | 0 | 0 | 1000 | 0 | 1 | | 0 |

| | s~ | ref(A~) | t~ | | s | ref(A) | t |
|---|---|---|---|---|---|---|---|
| Cu extr | 0.295 | 1 | **0.295** | Cu extr | 0.660 | 1 | **0.660** |
| Cu ref | 0.295 | 1 | 0.295 | Cu ref | 0.600 | 1 | 0.600 |
| PCB | 1.000 | 1 | 1.000 | PCB | 1.000 | 1 | 1.000 |
| Laptop | 1.000 | 1 | 1.000 | Laptop | 1.000 | 1 | 1.000 |
| Oil | 0.417 | 1.2 | 0.500 | Oil | 1.000 | 1.2 | 1.200 |
| Electr | 0.000 | 1 | 0.000 | Electr | 1.000 | 1 | 1.000 |
| Factory | 0.000 | 1 | 0.000 | Factory | 0.001 | 1 | 0.001 |
| Petrochem | 0.500 | 2 | 1.000 | Petrocher | 1.000 | 2 | 2.000 |
| Plastic | 1.000 | 1 | 1.000 | Plastic | 2.000 | 1 | 2.000 |