

Material Flow Analysis from Origin to Evolution

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Supporting Information

Number of pages – 12

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1. Expanded discussion of metal material flow analyses

Existing MFAs for the elements of the periodic table were the subject of an extensive review by Chen and Graedel (2012). Since that review was completed, a number of other MFAs have been published. It is not appropriate in this work to conduct an exhaustive review, but it is useful to list work of interest that was either not captured in the earlier publication or has appeared since that time. The entries in Table S1 are intended to indicate the breadth of MFAs that can serve as sources of information on MFA structure and analysis.

Although the individual elements (mostly metals) are the most common subject of MFA material studies, not all of the elements have thus far been addressed in MFAs, as can be seen from the compilation of Chen and Graedel (2012) and of Table S1. None of the noble gas cycles have been studied, nor have the halogens save chlorine (which sees significant industrial use). Among the alkali metals, only lithium has been investigated. Of the alkali earth metals, calcium and barium remain unstudied. Chemists have quantified much of the life cycles of hydrogen, carbon, nitrogen, oxygen, and sulfur in the atmosphere, but quantification of the uses of those elements within human technology and society awaits analysts. Even one of the transition metals – scandium – awaits a cycle analysis.

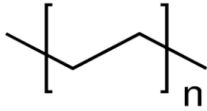
Table S1. Notable material flow analyses since 2012 for specific elements

3	Li	Talens Piero, 2013	45	Rh	Nassar, 2015
4	Be		46	Pd	Laner et al., 2015
5	B		47	Ag	Gsodam et al., 2014
6	C	Le Quere et al., 2018	48	Cd	Cha et al., 2013
7	N	Domene and Ayres, 2001	49	In	Werner et al., 2018
8	O		50	Sn	
9	F		51	Sb	
10	Ne		52	Te	Kavlak and Graedel, 2013b
11	Na		53	In	
12	Mg		54	Xe	
13	Al	G. Liu et al., 2013	55	Cs	
14	Si		56	Ba	
15	P	Cordell and White, 2014	57	La	
16	S	Ayres and Ayres, 1998	58	Ce	
17	Cl	Han, et al., 2014	59	Pr	Guyonnet et al., 2015
18	Ar		60	Nd	Sekine et al., 2016
19	K		62	Sm	
20	Ca		63	Eu	Ciacci et al., 2018
21	Sc		64	Gd	
22	Ti		65	Tb	Guyonnet et al., 2015
23	V	Zhang et al., 2014	66	Dy	Sekine et al., 2016
24	Cr		67	Ho	
25	Mn		68	Er	
26	Fe		69	Tm	
27	Co		70	Yb	
28	Ni	Zeng et al., 2018	71	Lu	
29	Cu	Soulier et al., 2018	72	Hf	
30	Zn	Meylan and Reck, 2017	73	Ta	Deetman et al, 2018
31	Ga	Meylan et al., 2017	74	W	Leal-Ayala et al., 2015
32	Ge	Licht et al., 2016	75	Re	Meylan et al., 2017
33	As	Shi et al., 2017	76	Os	
34	Se	Kavlak and Graedel, 2013a	77	Ir	Nassar, 2015
35	Br		78	Pt	Nassar, 2015
36	Kr		79	Au	
37	Rb		80	Hg	Ayres and Ayres, 1999
38	Sr		81	Tl	
39	Y		82	Pb	
40	Zr		83	Bi	
41	Nb		90	Th	
42	Mo		92	U	
44	Ru	Nassar,2015			

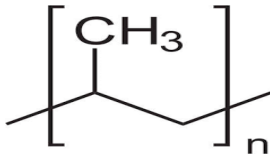
2. Expanded discussion of polymer material flow analyses

a. Molecular structures of common polymers (in order of molecular weight of monomer)

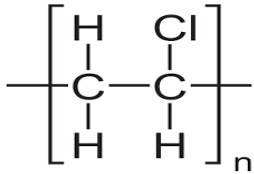
i. Polyethylene (PE)



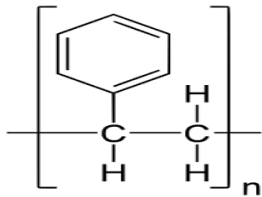
ii. Polypropylene (PP)



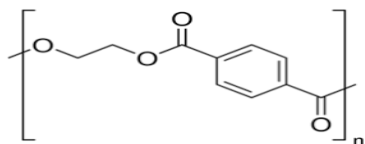
iii. Polyvinyl chloride (PVC)



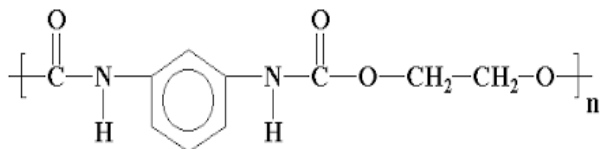
iv. Polystyrene (PS)



v. Polyethylene terephthalate (PET)

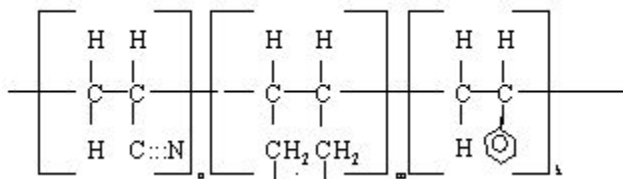


vi. Polyurethane



vii. Acrylonitrile butadiene styrene (ABS)

ABS acrylonitrile butadiene styrene (Terpolymer- addition)



b. Relative rates of production of common polymers

Table S2. Global production rates (2015) of common polymers (Geyer et al., 2017)

<i>Polymer type</i>	<i>Production (Tg/yr)</i>	<i>Year</i>	<i>Reference</i>
PE	116	2015	Geyer et al., 2017
PP	68	2015	Geyer et al., 2017
PVC	38	2015	Geyer et al., 2017
PS	25	2015	Geyer et al., 2017
PET	33	2015	Geyer et al., 2017
PUR	27	2015	Geyer et al., 2017
ABS	11	2016	Plastics Insight, 2019

c. Example of a quantified cycle of a common polymer

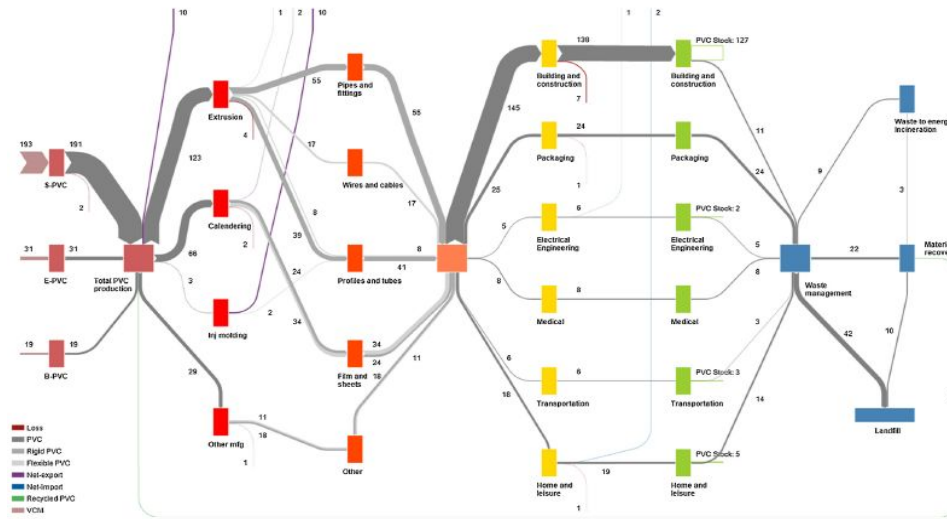


Figure S1. The aggregated European cycle of PVC, 1960-2012 (Ciacci et al., 2017)

d. Published MFA analyses for common polymers

As of the date of this review, there are few published MFA analyses for the common polymers or common polymer uses. However, complete cycles for Europe are available for all of the principal industrial polymers except PUR, and a dynamic cycle for the United States covers the years 1996-2007 (Table SI-2). Additionally, partial cycles that have useful content include those of Patel et al. (1968; PE, PP, PVC, PS), Zhou et al. (2013; PVC), Van Eygen et al. (2017, polymer use in products), and Levi and Cullen (2018, PE, PS, PET).

Table S3. Polymer MFA analyses as of the end of 2018

<i>Polymer</i>	<i>Venue</i>	<i>Year(s)</i>	<i>Reference</i>
PE (all types)	Europe	2014	Kawecki et al. (2018)
PP	Europe	2014	Kawecki et al. (2018)
PVC	Europe	1960-2012	Ciacci et al. (2017)
PVC	Europe	2014	Kawecki et al. (2018)
PS	Europe	2014	Kawecki et al. (2018)
PET	United States	1996-2007	Kuczynski and Guyer (2010)
PET	Europe	2014	Kawecki et al. (2018)

3. Expanded discussion of fiber material flow analyses

a. Published MFA analyses for wood and wood-based fibers

As of the date of this review, only a few published MFA analyses for wood and wood-based fibers have thus far been completed; they are listed in Table SI-3. Additionally, partial cycles that have useful content include those of WBCSD (2015, fiber recycling), O'Brien and Bringezu (2018, fiber products), and Spruce-Up GE³LS (2018, spruce fiber in Canada).

Table S4. Wood and wood-based MFA analyses as of the end of 2018

<i>Polymer</i>	<i>Venue</i>	<i>Year(s)</i>	<i>Reference</i>
Wood	United States	2014	AFPA (2015)
Wood	Europe	2011	Mantau (2015)
Wood (spruce)	Canada	2017	Spruce-Up GE ³ LS, 2017
Paper	Global	2012	Van Ewijk et al. (2018a)
Paper	Global	2012	Van Ewijk et al. (2018b)

b. Example of a quantified cycle of a common fiber

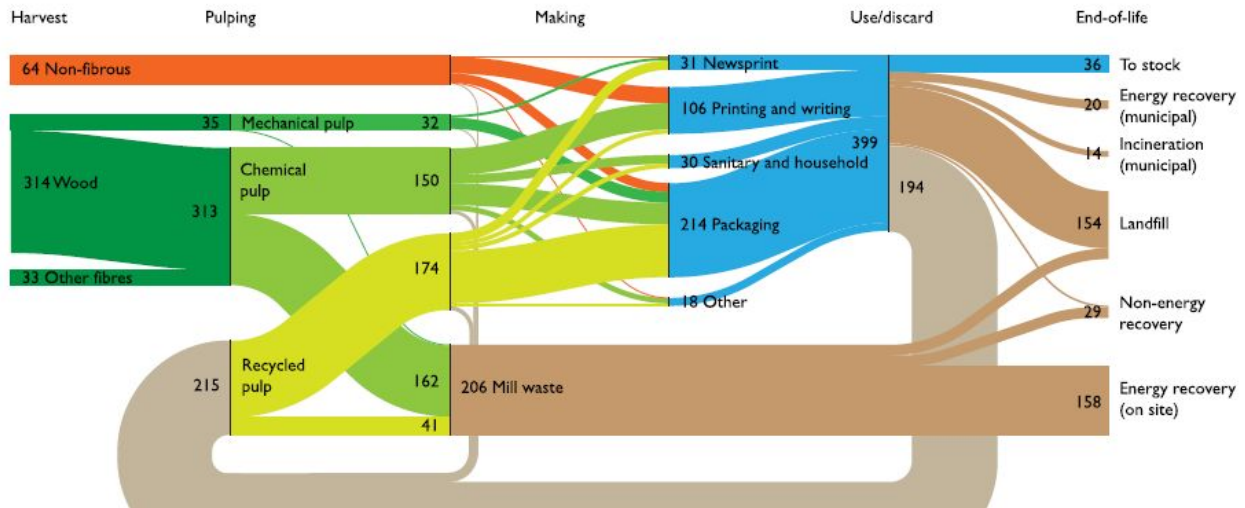


Figure S2. Global paper flows, 2012 (Tg) [Van Ewijk, 2018a].

4. Composite Materials

To date it appears that only a single MFA for composite materials has been produced, that of Lefeuvre et al. (2019) for carbon fiber reinforced polymers. It is reproduced below.

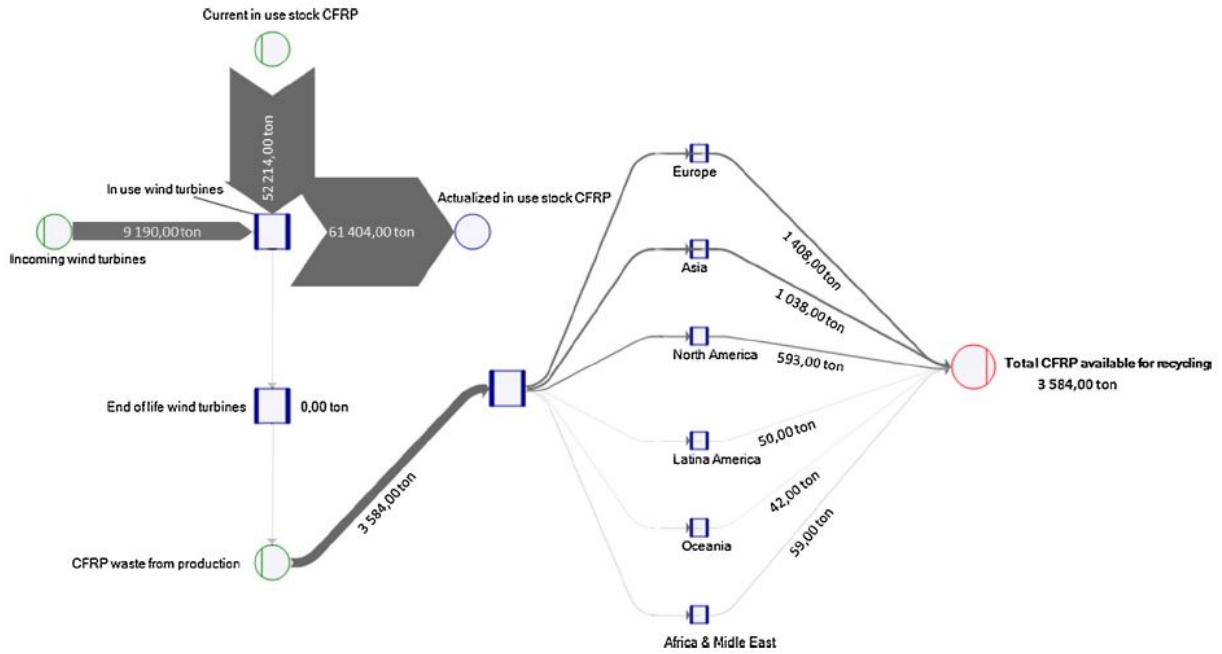


Figure S3. Carbon fiber reinforced polymers, global, 2017 (Lefeuvre et al., 2019).

5. Discussion of construction material flow analyses

Although the annual flows of construction materials (sand, crushed stone, cement) are larger than those of metals, polymers, or fibers, the complete lack of recycling of those components does not permit the construction or analysis of MFAs.

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