

Methods for Estimating Secondary Material Production through Sector-Level Recycling Approximation

Abstract: Given sectors see different polymer distributions and lifecycle duration expectations, the lack of comprehensive regional reuse data complicates plastics production modeling by preventing researchers from estimating the amount of recycling available at each year. Therefore, this supplemental document demonstrates how material flow approaches may incorporate secondary production by offering methods to approximate propensities for each sector to use recycled materials. Finally, estimated longitudinal production data separated by type demonstrate use of these estimations.

Introduction

As discussed in prior work, important “data gaps” remain for plastics research (Wang et al. 2021). In particular, this study finds difficulty in compiling comprehensive region-level data on sector-level or polymer-level recycling propensities. To understand the modeling need for this crucial information, consider that:

- Material flow modeling cannot estimate sector-level recycling rates like, for example, what percent of packaging versus transportation is recycled.
- This lack of information on sector-level recycling then complicates understanding the availability of secondary material per polymer.
- Given the different time to end of life expectations and polymer ratios per sector, this ambiguity in polymer-level recycling availability complicates prediction of primary versus secondary production overall.

Though this stems from a lack of data regarding the application of secondary material, this document observes that researchers may still have some information regarding the ability for different sectors to incorporate secondary production and proposes a modeling method to estimate re-circulation of recycling into sector-level masses. It does this by approximating the propensities for recycling to enter into each regional sector using their polymer ratios.

Method

After laying out essential simplifying assumptions, this method first considers estimating the secondary polymer masses. Then, this document turns to secondary sector mass in both a fully domestic and trade context.

Assumptions

Before considering polymer mass, this study makes the following assumptions:

- **Assumption 1:** Recycling rate is estimated at the region level.
- **Assumption 2:** Yield loss is constant across regions, sectors, and polymers.
- **Assumption 3:** A regional sector's propensity to consume a primary polymer is the same as the propensity for that sector to consume a secondary polymer of the same type. In other words, secondary material can displace any primary material of the same polymer type with mass equivalency after **Assumption 1**'s yield loss.
- **Assumption 4:** All recycled material is reused except for **Assumption 1**'s uniform yield loss across all regions, sectors, and polymers. In other words, excluding yield loss, material indicated as recycled in the dataset is actually reused. Any waste which was collected as recycling but not actually reused is assumed to be captured in different EOL fates.
- **Assumption 5:** The propensities for end of life fate and for consumption sector are the same between domestic and traded material.

These assumptions are further explored below.

Fully domestic

This document first considers these calculations in a fully domestic context.

Polymer mass

Under **Assumptions 1 and 2**, consider the following where s is secondary mass, e is end of life mass, and l is yield loss:

$$s_{polymer|region} = e_{recycled|polymer|region} * (1 - l)$$

$$s_{polymer|region} = p_{polymer|recyclable} * p_{recycling|region} * e_{polymer|region} * (1 - l)$$

$$s_{polymer|region} = p_{polymer|recyclable} * p_{recycling|region} * e_{region} * p_{polymer|region} * (1 - l)$$

This derivation is called **Formula 1**. Note that, for thermosets, $p_{recyclable|polymer}$ would equal zero and $s_{polymer|region}$ also becomes zero.

Sector mass

This method then needs to determine the secondary mass per sector:

$$s_{sector|region} = \Sigma(s_{polymer|region} * p_{sector|polymer|secondary|region})$$

This relies on understanding the recycling propensity for a polymer per sector per region but this $p_{sector|polymer|secondary|region}$ is not currently well known. Therefore, **Assumption 3** states the following:

$$p_{sector|polymer|secondary|region} \approx p_{sector|polymer|primary|region} \approx p_{sector|polymer|region}$$

This yields the following whose terms are all known:

$$s_{sector|region} = \Sigma(s_{polymer|region} * p_{polymer|sector|region})$$

Continuing from **Formula 1**:

$$s_{sector|region} = \Sigma(p_{polymer|recyclable} * p_{recycling|region} * e_{region} * p_{polymer|region} * (1 - l) * p_{polymer|sector|region})$$

$$s_{sector|region} = (1 - l) * e_{region} * p_{recycling|region} * \Sigma(p_{polymer|recyclable} * p_{polymer|region} * p_{polymer|sector|region})$$

It is worth highlighting that the summation term determines the probability of mass being any polymer that is recyclable and in the target region / sector.

$$p_{recyclable|sector|region} * p_{sector|region} = \Sigma(p_{polymer|recyclable} * p_{polymer|region} * p_{polymer|sector|region})$$

Therefore:

$$s_{sector|region} = (1 - l) * e_{region} * p_{recycling|region} * p_{recyclable|sector|region} * p_{sector|region}$$

This derivation is referred to as **Formula 2**.

Regionalized sector recycling

This method continues with further consideration of $p_{recyclable|sector|region}$. This becomes:

$$p_{recyclable|sector|region} = \Sigma(p_{polymer|recyclable} * p_{polymer|sector|region})$$

This continues **Formula 2**:

$$s_{sector|region} = (1 - l) * e_{region} * p_{recycling|region} * \Sigma(p_{polymer|recyclable} * p_{polymer|sector|region}) * p_{sector|region}$$

This is referred to as **Formula 3** and is further discussed below.

Constraints

Note that, in practice, this operation happens with some limitations. First, a **Constraint 1** requires a delay (d) from reaching end of life to recirculating which is addressed by assuming that:

$$s_{sector|region|available}(y + d) = s_{sector|region}(y)$$

Additionally, this analysis uses an **Assumption 4** which expects all recycled material to be reused after yield loss. This gives rise to a **Constraint 2** extending from mass balance where all recycling must be used after yield loss. This results in a modified Formula 3 called **Formula 4**:

$$s_{sector|region|balance} = \frac{s_{sector|region}}{\Sigma s_{sector|region}} * e_{region} * p_{recycling|region} * (1 - l)$$

Trade

As regions may trade both waste and goods, this document next considers which secondary consumption should be expected for exports at end of life, starting with **Assumption 5**:

$$e_{region} = e_{region|domestic} - e_{region|exports} + e_{region|imports}$$

Continuing to consumption using the same **Assumption 5**:

- The consumption from waste imports are not added to the region of import but instead attributed to a global trade in secondary consumption.
- That global trade in secondary consumption is apportioned to importers relative to the size of their overall net production imports.

This consumption post-trade is formalized as follows where i is imports and $p_{export|region}$ is the production export propensity:

$$s_{sector|region|post-trade} = s_{sector|region} * (1 - p_{export|region}) + s_{sector|global} * \frac{i_{region}}{i} * \Sigma(p_{export|region} * s_{sector|region})$$

Note that, in practice, this would use $s_{sector|region|balance}$ to satisfy **Constraint 2**.

Circularity

Note that this document so far describes the determination of secondary consumption from primary waste but this process may repeat as recycled materials may recirculate again. This requires code to iteratively evaluate for these masses as it changes e_{region} and $p_{sector|region}$ per year. This additional step would involve “looping” this process but, instead of using primary waste as input, it uses secondary waste from the prior iteration. Put formally, consider the following where w is a function that determines new waste across sectors given a year using lifecycle distributions:

- If first iteration: $e_{region}(iter, year) = e_{region}(year)$
- If subsequent iterations: $e_{region}(iter, year) = w(s_{sector|region|post-trade}(iter-1), year)$

This becomes an iterative estimation and the number of iterations required depends on an acceptance criteria regarding the max percent error allowed. Note that the ceiling of this error comes from the case of a 100% recycling rate across all regions. Therefore, consider the following:

$$error < (1 - l)^{n_{iterations}}$$

Note that, at 20% yield loss, 99.9% accuracy is achieved after roughly 30 additional iterations:

$$error < (1 - 0.2)^{30+1}$$

$$error < 0.00099$$

Different yield loss rates would require adjustment of these parameters.

Implementation

Observe that some terms are held constant through time by sector and region:

$$c_{sector|region} = (1 - l) * \Sigma(p_{polymer|recyclable} * p_{polymer|sector|region})$$

Implementation could choose to precompute these values, further simplifying **Formula 3** as follows:

$$s_{sector|region} = e_{region} * p_{recycling|region} * p_{sector|region} * c_{sector|region}$$

This **Formula 5** may speed implementation.

Results

This study arrives at the following projections using $c_{sector|region}$ with a yield loss of 20% ($l = 0.2$) Further details including regional and underlying sector-level results are available in the interactive tool at <https://global-plastics-tool.org> (Pottinger et al. 2023). Note the remaining terms for **Formula 5** do change from year to year and programming may consider them displaced by some delay d as previously discussed.

Stacked area chart with global primary and secondary production. Values of $c_{sector|region}$ are provided for reference as RatioWithLoss using prior published sector-level polymer ratios (Geyer, Jambeck, and Law 2017):

Sector	Region	Ratio	RatioWithLoss
Agriculture	China	0.9122807018	0.7298245614
Agriculture	EU30	0.875	0.7
Agriculture	NAFTA	0.8571428571	0.6857142857
Agriculture	RoW	0.90625	0.725
Construction	China	0.8472222222	0.6777777778
Construction	EU30	0.8325123153	0.6660098522
Construction	NAFTA	0.7808988764	0.6247191011
Construction	RoW	0.82	0.656
Electronic	China	0.8387096774	0.6709677419
Electronic	EU30	0.8225806452	0.6580645161
Electronic	NAFTA	0.8888888889	0.7111111111
Electronic	RoW	0.8461538462	0.6769230769
HouseholdLeisureSports	China	0.4188034188	0.335042735
HouseholdLeisureSports	EU30	0.603960396	0.4831683168
HouseholdLeisureSports	NAFTA	0.8268398268	0.6614718615
HouseholdLeisureSports	RoW	0.6733333333	0.5386666667
Other	China	0.4666666667	0.3733333333
Other	EU30	0.6330275229	0.5064220183
Other	NAFTA	0.5070422535	0.4056338028
Other	RoW	0.5529411765	0.4423529412
Packaging	China	0.9854227405	0.7883381924
Packaging	EU30	0.9876237624	0.7900990099
Packaging	NAFTA	0.9821428571	0.7857142857
Packaging	RoW	0.9842105263	0.7873684211
Textile	China	1	0.8
Textile	EU30	1	0.8
Textile	NAFTA	1	0.8
Textile	RoW	1	0.8
Transporation	China	0.8	0.64
Transporation	EU30	0.7931034483	0.6344827586
Transporation	NAFTA	0.6933333333	0.5546666667
Transporation	RoW	0.7631578947	0.6105263158

Discussion

This discussion further considers the conceptual meaning of the derivation, limitations, and implications for implementation.

Conceptual meaning

To supplement mathematical derivations, consider this method conceptually. In this framing, **Formula 3** states that, after yield loss, the amount of recycled material in a region goes into each sector proportional to the mass of that sector which can use recyclable polymers. In other words, recycled materials are distributed proportionally to the ability for a sector within a region to receive recyclable materials. Then, given **Assumption 4**, this method’s **Formula 4** ensures all recycled material is actually used, closing the loop between production and end of life. One may observe that, by extension, sectors therefore produce secondary material in proportion to the amount of recycling they generate due to their polymer ratios but that these “recycling propensities” depend both on region and sector.

Limitations and future work

This document highlights future work regarding its five assumptions:

- **Assumption 1** could be relaxed by sectorizing $p_{recycling|region}$, requiring additional data collection but further improving model accuracy.
- **Assumptions 2 and 4** assume a constant yield loss but this could be relaxed by removing l and adjusting $p_{polymer|recyclable}$, a value which could also be regionalized.
- **Assumption 3** could be relaxed if recycling propensities become available per polymer by region, removing the approximation used above.
- **Assumption 5**: Could be relaxed by assuming a sector-level version of $p_{export|region}$.

This study does not currently have access to data required to take these steps, leaving opportunities for future work.

Conclusion

This document calls for additional study regarding polymer reuse at the regional sector level where lack of those detailed comprehensive data presents challenges to material flow modeling. However, the nature of policy making may require the expediency of an approximated approach or else data may become delayed beyond a realistic timeline needed for collective action given ongoing international treaty efforts (Jones 2023; Pottinger et al. 2023). Therefore, leveraging knowledge about polymer ratios and recyclability, this document offers a method for tracking those recirculated materials in absence of detailed observational information. This enables a more holistic understanding of secondary reuse and, despite reasonable approximations made by this method, the resulting projections still likely support timely practical policy decision making. These approaches are included in article

main text and the live version of <https://global-plastics-tool.org>, further building upon the underlying base model.

Works Cited

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