IEooc_Methods3_Exercise2: The lifetime of materials in the technosphere

Sample Solution

Goal: *Develop and solve a basic model of the recycling loop, define and calculate the lifetime of a material in the technosphere and the average number of life cycles.*

NOTE: *This exercise builds on IEooc_Methods2_Exercise3 and on the reading material IEooc_Methods3_Reading1, please check those first!*

Problem setting

The metal industries often claim that metals can be recycled indefinitely often, without loss of quality. Unfortunately, this claim is not true. The reasons are that a) our waste management industries cannot perfectly separate the different metal fractions from the waste streams, so that there is contamination with other metals in most cases, and b) there are losses at all stages of the recycling loop. When a unit of metal, like steel, passes through different product life cycles, it needs to flow through the recycling loop several times. Each time it passes through that loop, some more impurities accumulated and some more metal gets lost in obsolete stocks, dissipative losses, shredder and other waste management residues, and slag during remelting. [http://www.blog.industrialecology.uni-freiburg.de/index.php/2017/10/29/the-lifetime-of-materials-in-the-technosphere/]

In this exercise we will define two central indicators to measure the performance of a metal cycle: the lifetime of a material in the technosphere and the average number of life cycles. We will quantify them using a simplified lifetime model for three cases: aluminium beverage cans, construction steel, and a hypothetical closed loop system for automotive steel.

System definition

For this exercise we will apply the system definition of MaTrace Global (Pauliuk et al., 2017) with the following three simplifications: a) the lifetime is fix (no lifetime distribution, all products have the average useful lifetime), b) no re-use is excluded and c) fabrication scrap (aka prompt scrap aka new scrap) is not considered. With these simplifications a simple solution for the technical metal lifetime can be obtained using pencil and paper. For the full system the model can be solved using the publicly available MaTrace Global software (https://github.com/stefanpauliuk/MaTrace_Global).

The system definition is shown in Figure 1, it is based on the MaTrace model by Nakamura et al. (2014) and the concept of absorbing Markov chains (Eckelman and Daigo, 2008). The figure shows a system for closed loop recycling, with an exogenous input F_{0_5} to the use phase (1), the waste management industries (2), remelting (3), and manufacturing (4). The system describes the stocks and flows of one metal only, other metals and the product(s) itself are not considered. The model is dynamic, meaning that the flows are quantified for each model year. The in-use stock (1) links the present to the future: The future outflow F_{1_2} depends on the historic consumption. All processes but the use phases are modelled as instantaneous.

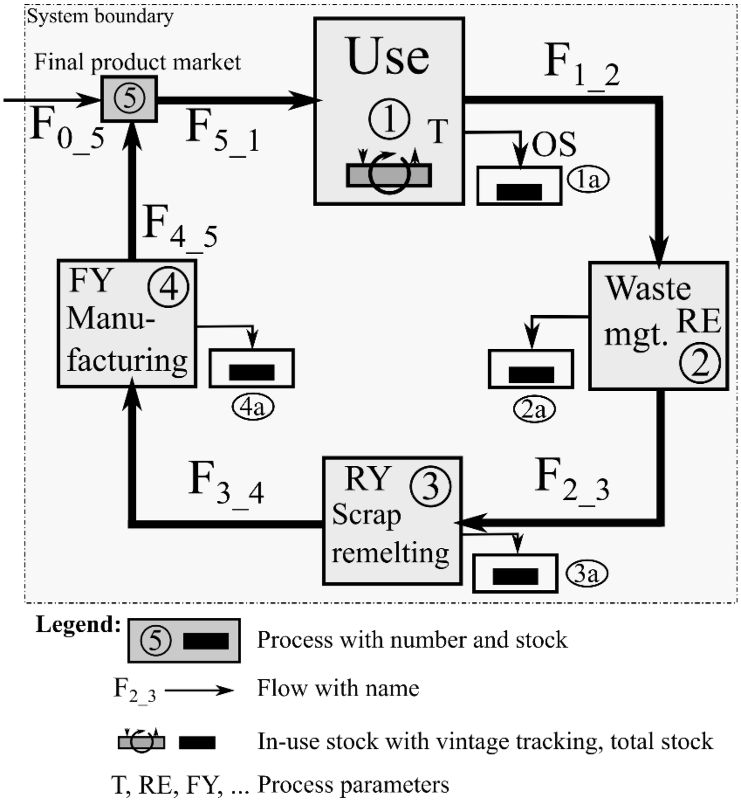

Figure 1. System definition for this exercise.

A number of process parameters are defined and values are gathered from the literature (Table 1). The parameter values reflect the real situation, with two exceptions: 1) No data could be found for the average cycling time of a beverage can, so 4 months was used, which includes the time lags of all steps in the cycle. 2) The assumed closed-loop recycling of automotive steel is hypothetical, as contamination with tramp elements is too high with current recycling technologies.

Table 1. Model parameters for the three cases. The parameter values reflect the real situation, with two exceptions: 1) No data could be found for the average cycling time of a beverage can, so 4 months was used, which includes the time lags of all steps in the cycle. 2) The assumed closed-loop recycling of automotive steel is hypothetical, as contamination with tramp elements is too high with current recycling technologies.

	Definition	**Aluminium (beverage can)**	**Steel (building)**	**Steel (passenger car)**
Lifetime T (yr)	Length of a single material life cycle	0.33	75	15
Obsolete stock formation OS (%)	$F_{1\_1a}/(F_{1\_1a}+F_{1\_2})$	0.04	0.1	0.09
Recovery rate of scrap RE (%)	F_{2_3}/F_{1_2}	0.95	0.86	0.85
Remelting yield RY (%)	F_{3_4}/F_{2_3}	0.97	0.97	0.94
Fabrication yield loss FY (%)	F_{4_4a}/F_{3_4}	0	0	0

Tasks and questions:

Assume that in model year 0 an amount of M_0 = 1 kg of metal was consumed in form of one of the three products (Flow F_{0_5}). There is no exogenous input to the system in any of the subsequent model years.

1) **Develop a (general) dynamic MFA model to quantify the amount of metal in the use phase (*S1*) at a given time t in the future! Assume that the lifetime is a fixed number of whole years (5, 18, …).**

   Solution: We first calculate the total efficiency of the recycling loop *C* by establishing a relation between F_{4_5} and the outflow from the in-use stock O = F_{1_2} + F_{01_1a}:

$$\begin{aligned}
F_{4\_5} &= F_{3\_4} - F_{4\_4a} = (1-FY)\cdot F_{3\_4} \\
&= RY\cdot(1-FY)\cdot F_{2\_3} \\
&= RE\cdot RY\cdot(1-FY)\cdot F_{1\_2} \\
&= \left[(1-OS)\cdot RE\cdot RY\cdot(1-FY)\right]\cdot O \qquad \text{Eq. (1)} \\
F_{4\_5} &=: C\cdot O
\end{aligned}$$

$$\text{where}$$

$$C = (1-OS)\cdot RE\cdot RY\cdot(1-FY)$$

Every time the product and the material(s) in it get discarded and recycled, the share of material that is recovered for the next life cycle is given by *C*. With the initial input of M_0 in the first model year the in-use stock *S1* equals to M_0 for the first *T* years, where *T* is the fixed lifetime. After T years, the product is discarded and $C\cdot M_0$ is recovered for the second life cycle, thereafter $C^2\cdot M_0$, then $C^3\cdot M_0$ for the fourth life cycle etc. (Eq. 2).

$$S_1(t) = \begin{cases} M_0, & 0 \le t \le T \\ C\cdot M_0, & T \le t \le 2T \\ C^2\cdot M_0, & 2T \le t \le 3T \\ C^3\cdot M_0, & 3T \le t \le 4T \\ \ldots & \\ C^{(n-1)}\cdot M_0, & (\mathrm{n}-1)T \le t \le \mathrm{n}T \end{cases} \qquad \text{Eq. (2)}$$

That means that the amount of material present in product life cycle n is $C^{(n-1)}\cdot M_0$. In the case of a fixed product lifetime *T*, the amount of material in the use phase changes in discrete steps, namely every *T* years, when part of the material enters a new life cycle through the recycling loop. After t years, the ordinal number *m* of the life cycle the material (or what remains of it) is in is given by

$$m = t \setminus T + 1, \quad \text{where} \setminus \text{is the integer division} \qquad \text{Eq. (3)}$$

For example, in model year *t=50* the material in a product with a lifetime *T=13* years is in its 4th life cycle (3+1).

The amount of material remaining in the use phase is then just the combination of equations 2 and 3 for *m* = *n*.

$$\boxed{S_1(t) = C^{(t \setminus T)} \cdot M_0} \qquad \text{Eq. (4)}$$

Figure 2 shows the decay of the material in the use phase over time, for a fixed product lifetime.

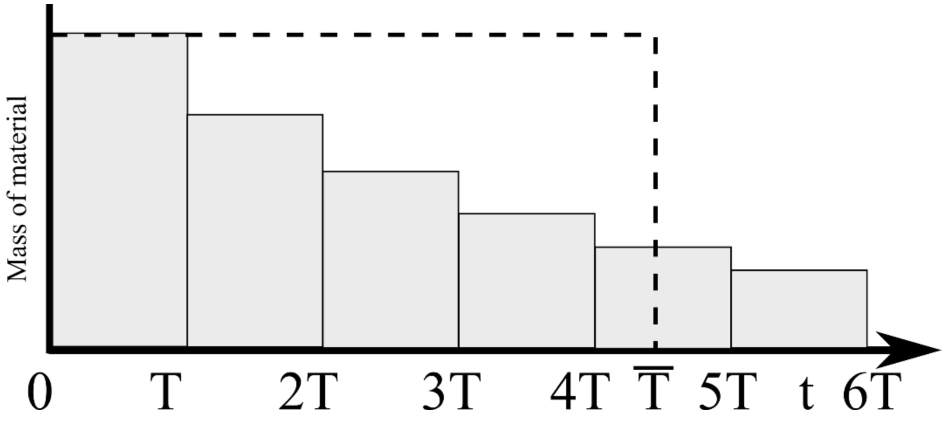

Figure 2. Material in use phase over time (grey area). The hypothetical average technical lifetime of the material is also indicated (dashed box).

2) Determine the average lifetime of the metal in the technosphere for each of the three cases listed in Table 1!

Figure 2 can be read vertically, showing how much material is present at a certain time *t*. It can also be read horizontally, then showing how long the different fractions of the material originally consumed last in the use phase before they are lost in the recycling loop. From the horizontal perspective it becomes clear that the average technical lifetime of a unit material is the width of the dashed box. This area must be equal to the area of all grey bars, because this area denotes the total service life x mass that is present in the system.

The area equality reads then

$$M_0 \cdot \bar{T} = M_0 \cdot T + C \cdot M_0 \cdot T + C^2 \cdot M_0 \cdot T + C^3 \cdot M_0 \cdot T + \ldots = M_0 \cdot \frac{1}{1-C} \cdot T \qquad \text{(Eq. 5)}$$

The rightmost term shows the limit value of the geometric series for the powers of *C*. It exists for all $0 < C < 1$. Dividing by M_0 yields the average lifetime

$$\boxed{\bar{T} = \frac{1}{1-C} \cdot T} \qquad \text{(Eq. 6)}$$

3) **Determine the average number of life cycles *N* of the metal in the technosphere for each of the three cases listed in Table 1!**

The average number of life cycles is just the factor scaling T to $\bar{T}$.

$$\boxed{N = \frac{1}{1-C}} \qquad \text{(Eq. 7)}$$

Table 2 shows the results for the three cases.

Table 2. Recycling loop efficiency *C*, technical material lifetime $\bar{T}$, and average number of life cycles *N*.

	Definition	**Aluminium (beverage can)**	**Steel (building)**	**Steel (passenger car)**
Lifetime T (yr)	Length of a single material life cycle	0.33	75	15
Recycling loop efficiency *C*	Share of End-of-life material that re-enters the use phase as recycled material in a new product	0.885	0.751	0.727
Average number of life cycles *N*	Average number of life cycles of the material in different products	8.67	4.01	3.66
Technical material lifetime $\bar{T}$	Average residence time of material in the technosphere	2.86	300.94	54.96
Technical material lifetime $\bar{T}$ acc. to Pauliuk (2017)	Average residence time of material in the technosphere	---	280	110

4) **Interpret your findings!**
The overall recycling loop efficiency is highest for beverage cans (ca. 89%) and 73-75% for the steel in buildings and cars. Correspondingly, the average number of life cycles is only around 4 for steel in buildings and cars (and not infinite!), and around 9 for Al in beverage cans. Even for beverage cans, which now have one of the most mature and close recycling systems, the material does not last longer than 9 life cycles before it is lost to the environment, landfills, and slag piles. Reduction of obsolete stock formation, better scrap recovery (dismantling instead of shredding) are needed. It is important to note that material quality did not enter the model, and tramp element contamination often represents and additional hindrance to closing material loops.

Since the lifetime of the four product spans several orders of magnitude, the average technical lifetime ranges from less than 3 years for beverage can aluminium to about 55 years for steel in passenger cars and about 300 years for steel in construction.

It must be kept in mind that these numbers are derived from a very simple model. A more sophisticated approach to determining the average technical lifetime is to apply the MaTrace model, which contains a lifetime distribution, different recycling and remelting technologies, and the recycling of fabrication scrap. A comparison shows that our simple estimate for steel comes quite close to the MaTrace result, whereas for cars we were of by a factor of 2. The lifetimes where the same in both cases, but for that particular calculation with MaTrace I did not consider obsolete stock formation of vehicles.

Questions 2 and 3 were introduced to the industrial ecology community by Daigo et al. (2005).

References:

Daigo, I., Matsuno, Y., Ishihara, K.N., Adachi, Y., 2005. Application of Markov chain model to analyzing the average number of times of use and the average residence time of Fe element in society. Tetsu to Hagane (Journal Iron Steel Inst. Japan) 91, 159–166.

Eckelman, M.J., Daigo, I., 2008. Markov chain modeling of the global technological lifetime of copper. Ecol. Econ. 67, 265–273.

Nakamura, S., Kondo, Y., Kagawa, S., Matsubae, K., Nakajima, K., Nagasaka, T., 2014. MaTrace: Tracing the Fate of Materials over Time and Across Products in Open-Loop Recycling. Environ. Sci. Technol.

Pauliuk, S., 2017. Critical Appraisal of the Circular Economy Standard BS 8001:2017 and a Dashboard of Quantitative System Indicators for its Implementation in Organizations. Resour. Conserv. Recycl. Forthcoming.

Pauliuk, S., Kondo, Y., Nakamura, S., Nakajima, K., 2017. Regional distribution and losses of end-of-life steel throughout multiple product life cycles—Insights from the global multiregional MaTrace model. Resour. Conserv. Recycl. 116, 84–93.