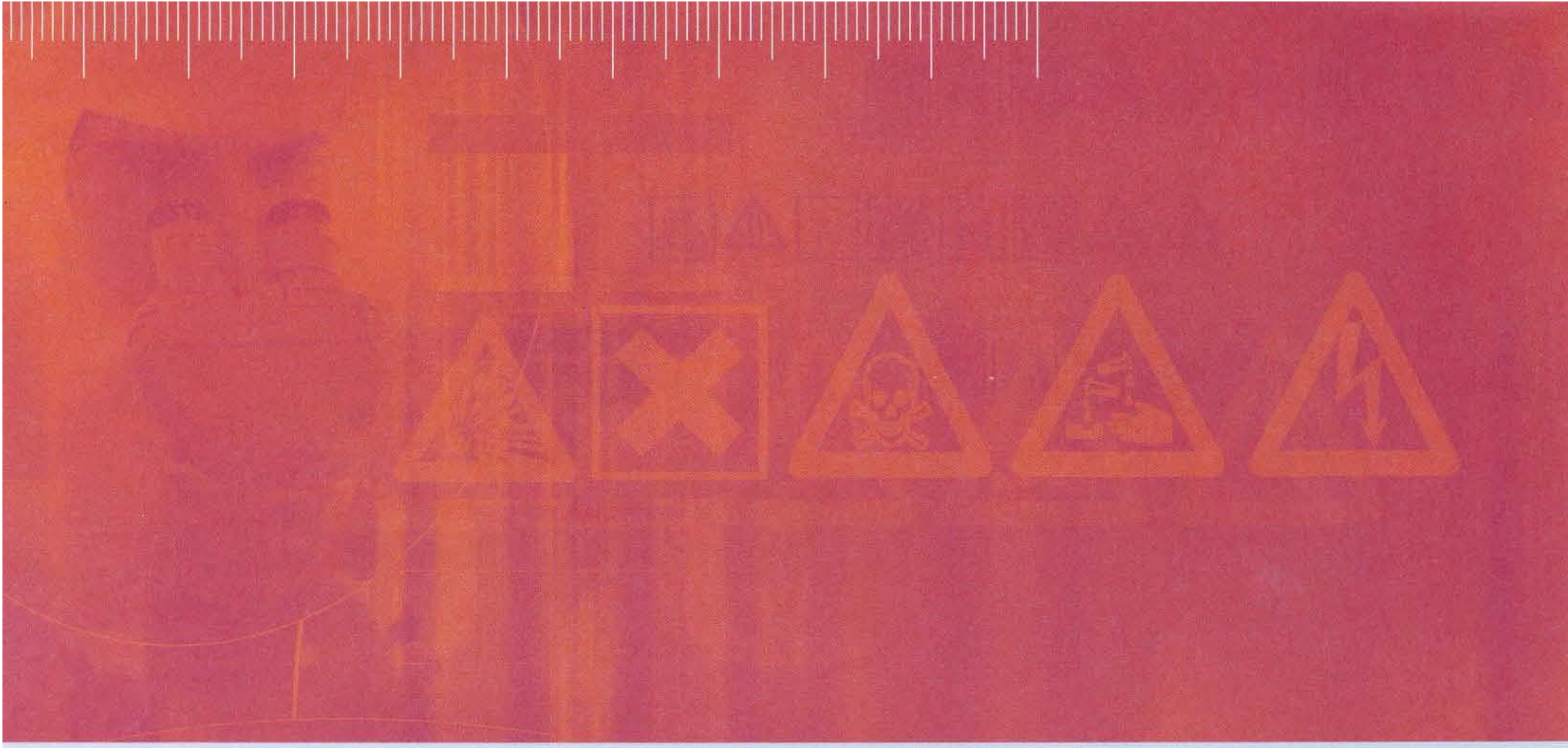

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Advantages and disadvantages of recycling materials containing hazardous additives: An economic approach and illustration with the case of soft PVC and DEHP.

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Advantages and disadvantages of recycling materials containing hazardous additives:

An economic approach and illustration with the case of soft PVC and DEHP

EDEN / EICB / DRC

INERIS

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Report prepared for: MTES, DGPR

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1. SUMMARY

The reuse of materials, especially plastics, is an attractive option in terms of promoting circular economy, resource efficiency and energy saving, and therefore in terms of reduction of greenhouse gases emissions and pollutants. However, recycling raises questions regarding the potential risks to human health and the environment when hazardous additives of plastics are recycled, that without recycling would have been replaced by newer and less hazardous chemicals in new virgin materials.

A special case of this problem is the current European decisions concerning the phthalate DEHP in the context of its use as a PVC plasticizer. The question arises in the context of REACH, whether recycling is sufficiently environmentally attractive to warrant granting companies permission to continue to recycle PVC containing DEHP.

We propose in this work a simple and integrated modeling framework to assess the total external cost of using a plastic material, taking into account the health and environmental impacts of all industrial steps (virgin plastic production, incineration and recycling) , including the effects on health of any hazardous additives during the recycling of plastic. Under various assumptions on future market growth rate, of incineration and of recycling, it is possible to project and compare recycling strategies of the material.

We then apply this model for illustrative purposes to the case of soft PVC in France, establishing a baseline scenario, and comparing it with two scenarios: one with a faster increase in recycling rates, and another in which recycling is stopped. First, the model estimates that the total annual external costs of the French market in flexible PVC food are of an order of magnitude ranging in the hundreds of million euros (30% of the annual value of the flexible PVC market).

We show that the promotion of recycling results in an initial increase of the total external costs. However, after a certain time (varying depending on parameters settings) there will be an overall positive and growing benefit to increase recycling rates. However, the time when increased recycling becomes positive despite the extension of the presence of DEHP is highly variable, and depends on the model parameters, essentially on the values of external costs of DEHP. Overall, differences between scenarios remain small anyway in relative terms (1 to 2% of the cumulative total external costs over the period analyzed (20 years)), if possible extreme values for the health costs of DEHP are left aside.

We also simulated a fictional scenario in which recycling is stopped, which causes a significant increase in long-term total external costs, also in an order of magnitude very dependent on the unit value of health damage of DEHP.

This type of models and calculations is useful to show the temporal dynamics and long-term trends, compare the short term. In particular; it suggests that recycling is always beneficial in the long run.

The uncertainty regarding the external costs of DEHP would however be reduced and may allow a more operational use of the model to help decision, if, instead of an illustrative case including all soft PVC, we worked on a set of well-defined articles, because then the concentrations of DEHP, and the exposure from articles and associated health impacts could be better clarified.

A more operational use in policy guidance for a particular material involves a number of developments:

- First, improvement of data on the health impacts of additives in materials. We remind that beyond the case of DEHP, additives of a given material are very numerous, and additives that will replace the old "banned" additives are often even less well known.
- The development of a refined modeling framework, taking into account the typology of products with differentiated service lives, and representing the mix of their flow during recycling. The report indicates the way forward in this direction.

Finally, the development of such models would be useful to study the conditions for a sustainable circular economy. Indeed, introducing recycling, even intensively, in the economy, does not guarantee that external costs of materials will remain what is bearable for man and the environment. Developing models capable of quantitative projections in the very long term, could help to set recycling targets more likely to comply with long-term environmental and health constraints. This would be similar to what is done for the purposes of limiting greenhouse gas emissions in the area of climate change.

2. INTRODUCTION

Plastics are made largely with fossil resources, and a wide range of chemicals are usually added to the polymer to provide them various physical and optical properties.

The reuse of materials, especially plastics, is an attractive option in terms of promoting circular economy, resource efficiency and energy saving, and therefore in terms of reduction of greenhouse gases emissions. Moreover, the reuse may also prevent the emission of pollutants in air and water associated with the manufacture of virgin materials or with the incineration of used plastic articles. It will also contribute to limiting the debris of plastics and microplastics in aquatic and terrestrial environments.

However, recycling raises questions regarding the potential risks to human health and the environment when hazardous additives for plastics are recycled that otherwise would have been replaced by newer and less hazardous chemicals in the new virgin materials.

It is therefore useful to evaluate all the pros and cons of recycling, namely firstly the risk for workers exposed to hazardous chemicals during recycling operations, or consumers in the use of recycled items, and also its environmental benefits.

The European Union encourages recycling as one of the key aspects of its circular economy strategy (European Commission, 2015), and in particular has set recycling targets for municipal waste and packaging of 65% and 75% in 2030 in the European Union. Industry has also taken initiatives to recycle plastics. In 2015, 514,913 tons of PVC waste were recycled as part of VinylPlus (VinylPlus, 2016) and the goal is to recycle 800,000 tons of PVC in the EU by 2020 each year.

EC's circular economic strategy recognizes that to promote demand for recycled plastics, confidence in the quality of these materials is necessary, and the development of quality standards for secondary materials (especially plastic) is scheduled for 2018 (European Commission, 2015). Not only the technical quality, but also the health and environmental safety should be covered by these standards, to strengthen consumer confidence. Therefore, the EC also foresees the development of analytical methods to improve the monitoring of chemicals of concern in recycled products, and a specific strategy for plastics in 2017. Such a strategy must be supported by methods allowing to assess the global environmental performance of recycling plastic materials.

A special case is that of ongoing decisions regarding the phthalate DEHP in the context of its use as a PVC plasticizer. The question is, in the context of REACH, whether the interest of recycling justifies giving companies authorization to continue to recycle PVC containing DEHP. ECHA committees have so far estimated that there were qualitative arguments in favor of such an authorization. In contrast, the European Parliament opposed this decision in a resolution, stating in particular that "recycling is not to justify the continuation of the use of existing hazardous substances" (European Parliament, 2015). This example shows the importance of developing an analytical framework that tries to exceed qualitative position statements.

We propose in this work a first integrated modeling framework to assess the total external cost of using a plastic material, taking into account the health and environmental impacts of all industrial steps (virgin plastic production, incineration and recycling), also including the health effects of recycling hazardous additives in recycling of plastic.

Under various assumptions on future market growth rate, of incineration and of recycling, it is possible to project and compare recycling strategies of the material.

Impacts to be considered being of a different nature (climate, air pollution, health impact of additives), we use environmental economics techniques to monetise all impacts on health and the environment and calculate the total cost of external market supply. For that purpose, we use reference published reference economic values of the impacts of pollutants and greenhouse gases.

We then apply this model for illustrative purposes to the case of soft PVC in France, establishing a baseline scenario that we compare with two other scenarios: one with a faster increase in recycling rates than in the baseline scenario and another with a stop in recycling. Monetization also makes it possible to compare the respective weights of the different impact categories in a scenario, and between scenarios.

3. A MODEL OF THE TOTAL EXTERNAL COST OF A MATERIAL

In this part, we establish a first integrated modeling framework to assess the total external cost of using a material, taking into account the health and environmental impacts of all industrial steps (virgin plastic production, incineration and recycling) , and in particular the health effects of recycling potentially hazardous additives during the recycling of the plastic[1].

The goal is to perform a calculation on the scale of a market and taking into account the temporal evolution of external costs. Variations in the production rate, incineration, recycling[2](Ie in the stock of material present on the market), as well as changes in the content of additives in the hazardous material are modeled. The model therefore combines: consideration of the life cycle, a flow model of the material and additives, and an economic approach to health and environmental externalities.

A scenario representing a marketplace is characterized by variable and the following parameters:

- Q0 is the initial stock of plastic on the market (at time t = 0) and (t) its evolution in time, this variable is calculated by the model (based on a mass balance, see below)
- The parameter C0 is the average background concentration of the hazardous additive in this stock and C(t) its evolution over time, calculated by the model. For simplicity, we consider in this report a single additive, however, if more additives are of concern, their external costs can be integrated on the same principle. It is also assumed for simplicity that the additives of the virgin material are negligible compared danger and therefore are not to be modeled. However, dangerous additives in the virgin material could be included in the model without difficulty (see Appendix 7.3).

  C(t).Q(t) is the amount of the additive on the market at time t, and we assume that the health impacts[3] and therefore the external costs of this additive is proportional to the amount (more details below).

[1] Recycling can in some cases totally or partially remove the additive, but we put ourselves in the event that this is not the case (removal rate during recycling could be introduced if needed).

[2] Other processes of end of life could be added, but the model has been adapted here to the data available for PVC flexible / DEHP case study.

[3] An environmental impact could be introduced similarly, but for simplicity and, in view of an application in the case of PVC / DEHP, it will not be considered here.

- i(t), v(t) and r(t) are respectively the incineration rate, production rate of virgin material, and recycling rate, expressed as a ratio with respect to the stock. They are the fractions of the stock that are respectively incinerated, produced and recycled per unit of time. The model the following type of formulation i(t)=i*t+i0 with i0 the capacity initial of incineration, but non-monotonic relationship could also be represented. The three rates are interdependent and are parameters that will be calibrated simultaneously in a consistent manner, to reproduce the observations of the quantities produced annually, incinerated, recycled, and of the annual consumption of the material (see below section 4.3).
- T is the average lifespan of articles made from the material under study on the market. Still to present a simple model, one category of products is taken into account. Several categories of products with distinct service lives and separate mixing rate during recycling can be represented with greater realism, but at the cost of greater complexity, more computational resources, and an increased need for data (see Annex 7.3).
- The respective unit external costs of incineration, production of virgin materials, and recycling (per unit mass of material). In the present work, these parameters are assumed to be constant, but to represent future environmental progress in the technologies used[4], one could also assume that they vary over time (decrease if environmental progress).
- Finally, another constant parameter is the unit cost of the external additive[5] (Per unit mass of the additive on the market and unit time)

The purpose is to express, given the model parameters (Q 0, C0, i, i0, v, v0, r, r0, T, unit external costs), the total external cost EXT(t) to supply the market material from t0 to time t.

EXT (t) is the sum of

1) ExtADD (t): external costs associated with the presence of additive(s) on the market because of the recycling, since t=0.

2) ExtPRI (t), the external costs of production operations, recycling and incineration, since t=0.

Some remarks on the main limitations and assumptions in this calculation:

All the external costs related to the supply of material stock before t = 0 are not calculated. This would require knowing the history of the incineration rate, production and recycling rates, and the history of introduction of the additive on the market. The additional uncertainty is not justified, especially as the model will be used for comparisons between different future scenarios in which these past costs will not intervene.

[4] Future knowledge in the damage caused by emissions of these processes could also motivate the temporal evolution of these parameters.

[5]Several additives may be included without change in methodology. However, in view of the application cases, this has not been done as part of this work.

While taking them into account would not present a methodological difficulty, in this simplified model, we considered an isolated market (or global), with no exports or imports of material.

This omission does not necessarily have consequences for the imported materials since, from the perspective of environmental footprint, the external costs of production (or the recycling process) must be assigned to the final consumer market. So we will consider implicitly all virgin plastic used as manufactured on the market being modelled.

External cost ExtADD (t) of the additive:

At each instant u (between 0 and t) the amount dq(u) = r(u)Q(u)C(u) of the additive is introduced to the market by recycling between u and u+du. Its external cost between u (when released) and when it is either incinerated or recycled again (and in the latter case, reintroduced on the market) is proportional to the amount and time that the article that contains this quantity remains on the market[6] (According to ECHA approach for DEHP, which will be specified in section 4) and is given by:

$$\int_{\mathrm{u}}^{u+T} \mathrm{ADD.}\quad \mathrm{dq(u)}.\,ds \ \ (Eq.1)$$

Where ADD is the external cost of a unit mass of additive during a time unit.

The assumption is made here that the damage of the additive is, except regarding the discount rate, proportional to the amount put on the market, and to the time articles containing the additive remain on the market (ADD being the proportionality coefficient). The amount of additive on the market is an indicator of the magnitude of potential doses and the duration of presence of articles of the likelihood of exposure to individuals. If more detailed information would be available, eg if concrete effects on health (illnesses, ...) could be assessed quantitatively in relation to the concentration in the articles, the external costs could be expressed more specifically, and the monetary value of these health impacts quantified.

Therefore, the total external costs of all the additive introduced by recycling between time 0 and t is given by integrating the previous expression between 0 and t :

$$ADD.T.\int_0^t e^{-d.u}.\mathrm{r(u)Q(u)C(u)}.\,du \text{ (Eq.2)}$$

We have implicitly assumed that the additive is stable over time. It would be simple to introduce degradation kinetics of the additive in the model without methodological change. However, there is in general no reliable information to set the value of such a coefficient of degradation.

[6]We assume that the additive is destroyed during incineration. It would be possible to introduce, for additives emitted by incinerators, a specific term for their impact in the model.

As noted above, the import and export of material are not explicitly represented. The recycled material can be exported, and in this case the health effects of the additive will be integrated or not in the balance, depending on the geographical scope that one wants to take into account for the quantification of health impacts. If the fraction of recycled material which is exported is known, one may decide to introduce it as a multiplicative coefficient in Equation 2 above[7].

External costs of production, incineration and recycling:

Since the external cost of each of these processes is proportional to the amount of processed material, we have:

$$ExtPRI(t) = \int_0^t (I.i(u).\mathrm{Q(u)} + R.r(u).\mathrm{Q(u)} + P.v(u).\mathrm{Q(u)})du \quad \textit{(Eq.3)}$$

Where I, R and P respectively denote the external costs of incineration, recycling and of the production of a unit mass of material.

To compute the external costs ExtADD (t) and ExtPRI (t) one needs first the expressions Q(t) and Q(t).C(t) which are obtained using the mass balance of the material and additive (see Technical Appendix).

In the simple case with a single type of article, totally explicit expressions are obtained for the external costs and they are used to our application to DEHP and PVC soft that follows.

For a more realistic model representing the flow of several types of articles with mixing proportions known at the time of recycling, the calculation can be conducted according to the same principle as in the case presented here for only one type of article, but will require in general the use of numerical calculation methods (see Technical Appendix 7.3).

Finally, it is possible to introduce, as the external costs are estimated over a long-ranging future period of time, an economic discounting factor. We introduce the economic discounting factor in continuous time $e^{-d.t}$, where d> 0 is the discount rate (Machina MJ and WK Viscusi, 2014), and the above equations are modified as follows:

$$\int_{\mathrm{u}}^{u+T} e^{-d.s}.\mathrm{ADD.} \quad \mathrm{dq(u)}.ds \text{ (For Eq.1)}$$

$$\left(\frac{ADD}{\mathrm{d}}\right)(1 - e^{-d.T}) \int_0^t e^{-d.u}.\mathrm{r(u)Q(u)C(u)}.du \text{ (For Eq.2)}$$

$$\text{ExtPRI (t) = (for Eq.3)} \int_0^t e^{-d.u}(I.i(u).\mathrm{Q(u)} + R.r(u).\mathrm{Q(u)} + P.v(u).\mathrm{Q(u)})du$$

[7] The question can naturally more complex, for instance materials can be imported or exported while they are at some stage of their life, and only the remaining lifetime, if known, should be taken into account for the health impacts of the additive.

4. ILLUSTRATIVE APPLICATION TO THE CASE OF FLEXIBLE PVC AND DEHP

We now apply the model for illustration purposes, at the scale of France, to the calculations of external costs, for the case of soft PVC and its phthalate additive DEHP.

4.1 MODEL SETTINGS

4.1.1 ECONOMIC PARAMETERS

Unit external costs on the environment and health (effects related to air pollution, in particular) of production, incineration and recycling are evaluated based on available life cycle analysis. The health impact specifically associated with the presence of phthalates in soft PVC, is taken into account through the use and adaptation of the current assessment of the health risks of DEHP in flexible PVC carried out by ECHA.

External cost not related to DEHP, that is to say the unit external costs of implementation of the industrial processes (production, incineration or recycling) are obtained by multiplying the unit emissions of the industrial step by the external cost of the emitted pollutants (greenhouse gases, air pollutants). These external costs of air pollutants both include the environmental impacts of air pollution (mainly acidification and eutrophication) and their impacts on health.

As for DEHP, impacts on health (infertility, cryptorchidism[8], hypospadias[9]) are related to the reproductive toxicity of DEHP, and are supported by the male children whose mothers were exposed to DEHP. They were monetized by ECHA using estimates of direct costs to the health system, education and consent to pay (ECHA, 2017). ECHA has expressed these economic impacts in terms of €/(kg DEHP)/year. Because many assumptions are required to perform the calculations, ECHA warns that the estimates are highly uncertain, and concludes that they could vary from a minimum of 0.09 €/kg/year and a maximum of 4.29 €/kg/year, therefore a factor of up to 60. We use the geometric mean of 0.62 €/kg/year in the baseline, and the minimum and maximum values to illustrate the impact of uncertainties on DEHP on calculation results.

For virgin flexible PVC, we assume that the alternative plasticizer used has a negligible impact on health and the environment compared to DEHP. (ECHA, 2017) confirmed the availability of these alternatives.

[8] Cryptorchidism (undescended testicles) is the absence of one or both testicles in the scrotum and the most common birth defects in infants.

[9] Hypospadias is a common congenital malformation of the urethra in the male human urinary opening when it is not the located at the usual location on the penis head.

The set of reference values that follow was gathered from a previous study of INERIS (Brignon JM, 2015), to which the reader should refer for additional details on the selection of data sources. The main sources were the European Environment Agency and the University of Delft (external costs of air pollutants), and a synthesis by INERIS (for CO_2 costs), and ECHA (for costs of DEHP).

This set of data was collected in a previous study by INERIS (Brignon JM, 2015), to which the reader should refer for additional details on the selection of data sources.

Unit external costs of emissions are recalled in Table 1. For DEHP, the value in this table is the ADD parameter used in the model. For other pollutants, the values in Table 1 are then multiplied by the quantities emitted per kg of processed flexible PVC provided by LCA, to get the parameters P, R, and I. The reference values come from the European Agency Environment (EEA, 2014) (except for DEHP) and are used in the reference scenarios. Sensitivity values are used in sensitivity tests, and come from the research organization CE Delft, author of an important compilation of external costs (except for DEHP).

Pollutant	**Reference value**	**Value for sensitivity test**
CO_2	0059	0.1
PM_{10}	21.2	44
SO_2	15.9	16
NOx	5.5	11
Pb	965	437
Cd	31	136
Dioxins	27.107	54.107
DEHP	Minimum (€ 0.09/kg DEHP/year) and maximum (4,29€/kg DEHP/year)	

Table 1: External costs reference of the pollutants in € / kg except for DEHP

The unit external costs of industrial steps in the PVC life cycle which are used by the model (parameters P, R, I) are summarized in Table 2:

Step of life cycle	**External cost per kg of soft PVC**
Production	0.285
Incineration	0.198
Recycling	0,029

Table 2: Unit External Costs of life cycle steps of soft PVC (€ / kg of soft PVC)

4.1.2 OTHER PARAMETERS IN THE BASELINE SCENARIO

In this section we identify the parameters for the reference scenario, that will represent the initial state of the market in France and the continuation of past trends in end of life and recycling policies of flexible PVC.

The parameters to be selected are (Q 0, C0, i0ref, I ref, v0, vref, r0, ref, and T). The Instant "0" represents in all the following the beginning of 2017.

Q0 is the initial amount of flexible PVC on the market. It is an unobservable parameter and the available statistics provide only the quantities put each year on the market, or consumption figures. To estimate a probable figure for Q0, we used a simple historical stock model described in (Chapon V. et al., 2017) to transform the available time series of annual production of PVC data in total quantities on the market.

C0 is the initial concentration of DEHP in soft PVC in w/w: The available information summarized in (ECHA, 2017) indicates a current value of 0.08 (8%).

Initial rates of production, incineration and recycling of v0, i0 and r0 are fixed by the following: we consider that the current incineration and recycling rates in France are 40% and 20% (value for all non-mineral materials in 2011, expressed in terms of annual quantities incinerated and recycled respectively and divided by the annual quantities consumed)[10]. Flexible virgin PVC consumption rates for France has been estimated with the PVC industry organization data in Europe to 218/kt/year. We assume below that incineration is the only process for end of life.

Landfilling or composting are other potentially important destinations for materials and plastics, and could also be integrated into the model. However, no LCA could be found on the PVC landfilling, and it is therefore not explicitly included in the modeling framework.

[10] http://www.statistiques.developpement-durable.gouv.fr/indicateurs-indices/f/1929/1339/taux-recyclage-dechets-france.html

The parameters iref, vref and rref, which set the development of these rates are calibrated using two simultaneous constraints:

1) They are set by adjusting the average annual growth rate of the PVC market calculated during the study period to the value currently observed (2.5% is taken as an example in this case study)[11].

2) Their values reflect current baseline policy on incineration, recycling and incineration. For example, for this case study, we decided that iref <0 and rref>0, and that the annual recycling rate (initially 40%) is increasing by about 2% annually.

The parameter T representing the average lifetime of the articles, which is not involved in the material flow model (only in the calculation of external costs of additives, and evnetually in the model stock and flow for additives) can be deduced from the modeling results of the material stock, calculating the average time of renewal of the stock. With all parameters adopted above, including recycling rates and incineration, we get a value of T = 12 years. We compared this value with the one based on a census of observations of lifetime from real-life data, performed in the study (Chapon V. et al., 2017), which is 7 years. As (Chapon V. et al. 2017) indicate the large uncertainty of their result, the value of 12 deducted from other model assumptions seems plausible, and preferable for the consistency of modeling assumptions.

4.2 RESULTS FOR THE BASELINE SCENARIO

First, the annual total external costs, and breakdown by industrial processes and DEHP are presented in Figure 1, for the baseline scenario for the period 2017-2035. The total annual external costs of providing flexible PVC in France would be in the order of €85 million (for an annual consumption of about 200 tons / year over the period).

[11] To this end, the model also calculates the time series of annual quantities produced, incinerated and PVC recycled, from which we can calculate the time series of future annual consumption (annual production + recycling - incineration) and thus the annual growth rate of the PVC market, as well as the annual rates of change in the quantities produced, recycled and incinerated.

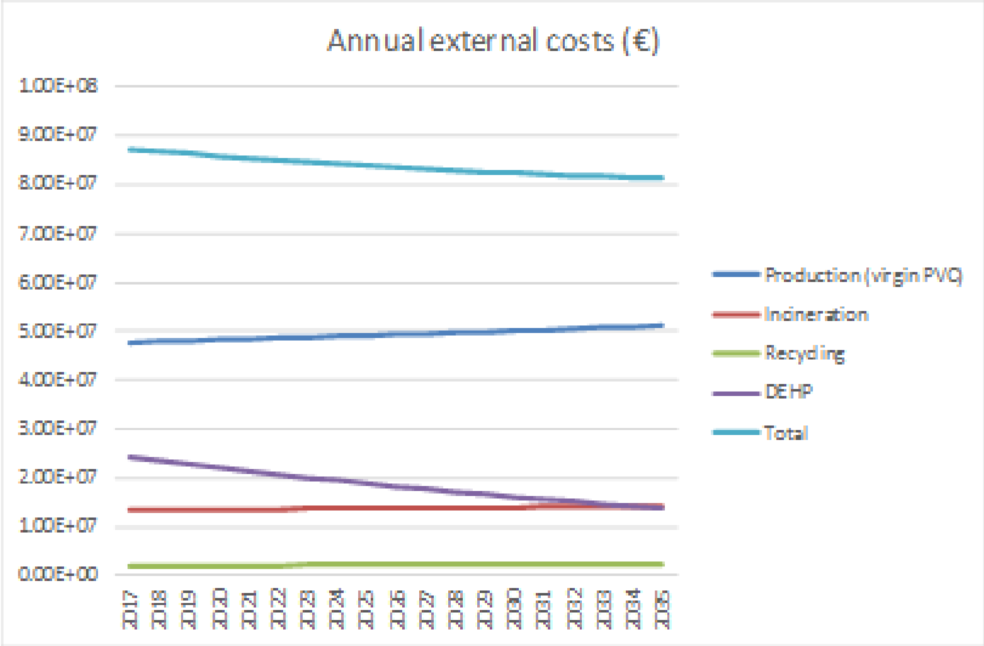

Figure 1: Annual external costs (baseline)

With the parameters used, the total external cost slightly decreases over time, despite a growing market, and despite the negative impacts of recycling in terms of DEHP (since it remains on the market). Therefore, in this case study, the current policy already seems to bring an overall improvement (here underestimated because the annual external costs of DEHP actually decreases slightly faster, see Appendix 7.2).

Note also that overall on study period, if assuming a price of flexible PVC around 1000 € / t in 2017 and annual inflation of 2% inflation, annual external costs represent approximately 30%, that is a significant part, of the value of the annual market of flexible PVC.

4.3 ILLUSTRATIVE SCENARIOS OF A CHANGE IN RECYCLING POLICY

4.3.1 SIMULATION OF INCREASED RECYCLING RATE

For this simulation, two scenarios are compared:

- the baseline with the initial baseline situation and trends, which has been described previously,
- and a similar scenario with increased recycling rates compared to the reference

We study the difference in total environmental performance (in terms of total external costs) between the two situations described in each scenario. We can therefore assess the relevance of increased recycling in a global sustainability perspective, taking into account both the negative impact (a longer presence of DEHP in the market) and positive impacts (better situation in terms of GHG and of pollution through recycling).

The baseline scenario and parameters have been described in Section 4.1

We define a second "scenario recycling +" (Q_0, C_0, i_0, i, v_0, v, r_0, r) with the same initial conditions and the same initial parameters as the baseline scenario, but with a faster increase in the recycling rate compared to baseline: $r(t) = r_0 + r * t$ with $r > ref$. It is considered that increasing the recycling rate is achieved via:

- a further reduction of the incineration rate and, therefore, in this scenario $i(t)=i_0 + (i_{ref}-(r-R_{ref}))*t$.
- a decrease in the virgin soft PVC production rate: $v(t)=v_0 + (V_{ref}- (r-R_{ref}))*t$.

In this way, the growth rate $v(t) - i(t)$ and the initial stock of soft PVC are identical between the two scenarios. Therefore, the total amount of soft PVC in products on the market is the same in both scenarios (for the sake of comparability, consumers have available to them the same amount of PVC items at any time in both scenarios).

We adjusted the model parameters “recycling + ", as an example, so that the annual recycling rate is increased by about 2% more per year compared to baseline.

Figure 2 below shows the calculation result of the relative difference in % of total external costs between the two scenarios.

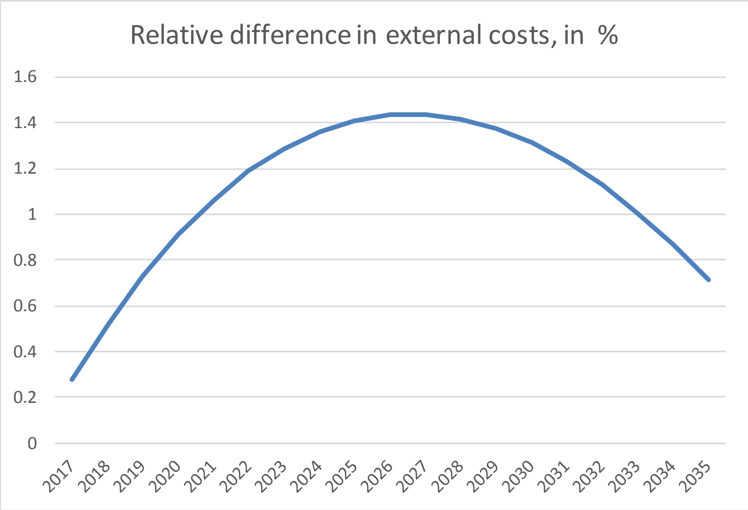

Figure 2: Relative difference in external costs between the "Recycling +" scenario and the reference scenario

The relative difference of the total external costs between the two models can be described as follows: from 2017 to 2027, the negative effects of recycling additional DEHP make it overall less favorable. However, in the longer term, the results prove to be in favor of the recycling scenario, because the concentrations of DEHP tend to decrease, while other environmental benefits remain comparable.

We also see that the difference is small, because the realistic changes that are simulated modify only marginally the production system and its impacts. It seems from these illustrative simulations, that marginal increases in recycling have only little overall environmental impact, and that they are positive in the long term.

4.3.2 SENSITIVITY STUDY

In the above calculation, it becomes positive after about 10 years to increase the recycling rate but sensitivity tests show that this result is extremely sensitive to certain key parameters, and relatively insensitive to others.

As is clear in Figure 3, the sensitivity to DEHP economic reference value is high and alters the conclusion of the simulation (due to the wide range of possible values for this parameter, given the uncertainty on knowledge of the health impacts of DEHP). This indicates a need to reduce uncertainty in knowledge of health impacts and their economic impact, with a view to decision support for recycling policies. We must also keep in mind that for several structural reasons mentioned above, the model overestimates the amount of DEHP remaining on the market.

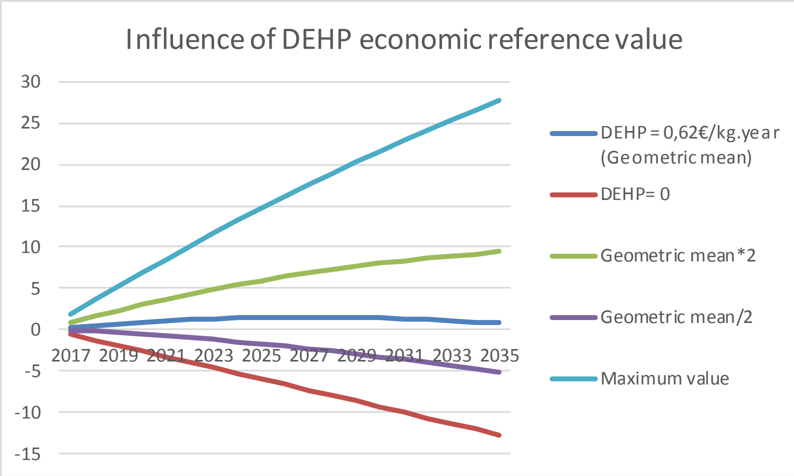

Figure 3: Sensitivity testing of results to the value of the unit external cost of DEHP

The difference in external costs, very low in the calculation with the central value of the parameter, can however become significant in the long run and for more extreme values of the unit external cost DEHP. The high uncertainty on the external costs of DEHP that is causing this dispersion in modeling answers would however be reduced if, instead of an illustrative case across the soft PVC, we worked on the case of wel-defined articles, because then the concentrations of DEHP and exposure conditions to articles and health impacts could be better clarified.

We also tested the sensitivity of results to external reference costs of CO_2 and of air pollutant (see Table 1). Sensitivity is important, but does not influence the conclusion (Figure 4).

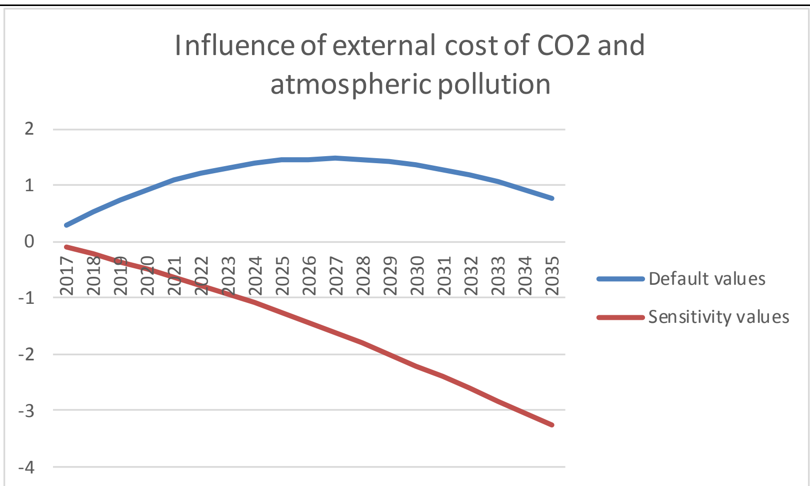

Figure 4: sensitivity test to the value of the external cost of CO_2 and air pollutants

Compared to the two previous tests, the sensitivity to the discount rate, usually high for the economic analysis of a long-term environmental problem is here comparatively low (test performed for the central economic baseline DEHP). However, the date from which the increase in recycling is a better policy, and the date of the inflection point of the curves, is largely influenced by that parameter.

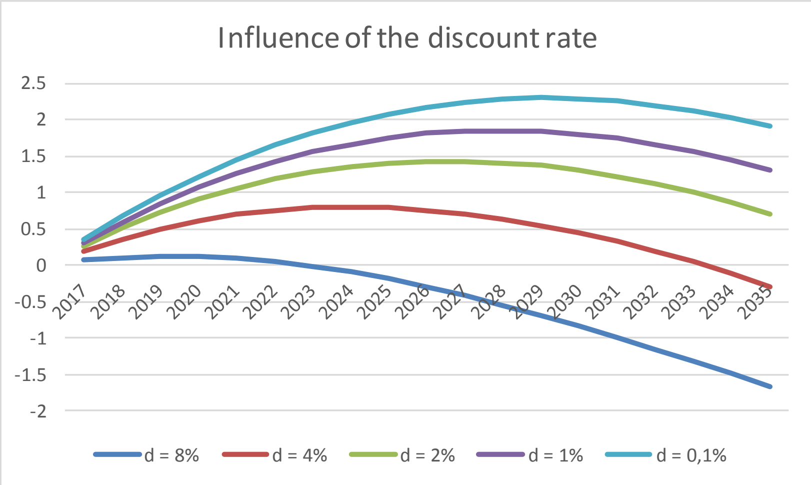

Figure 5: sensitivity test for the value of the discount rate

4.3.3 SIMULATION OF A STOP OF RECYCLING

Another interesting scenario is to assess the consequences of recycling from t = 0. Even purely theoretical, this scenario shows the maximum consequences of giving-up recycling that would be motivated by the hazards of DEHP.

We use the same baseline with the same initial conditions as above, and then we define a second scenario in which the recycling rate is canceled starting at t=0. For the same amount of PVC available for consumers in the baseline scenario, stopping recycling is offset by an equivalent increase at t = 0 in terms of virgin production and hence also of incineration.

Figure 6 shows the relative difference in% of total external costs between the two scenarios. Compared to the case of the previous study, the difference here is more important, indeed a sudden stop in recycling is a drastic change of policy. The scenario is calculated for the median value of the unit external cost of DEHP (approximately 0.6 €/kg DEHP /year). In the long run, the extra virgin production and incineration increasingly offset the initial advantage of having stopped recycling, and the "without recycling" policy would become globally unsustainable in the long-term.

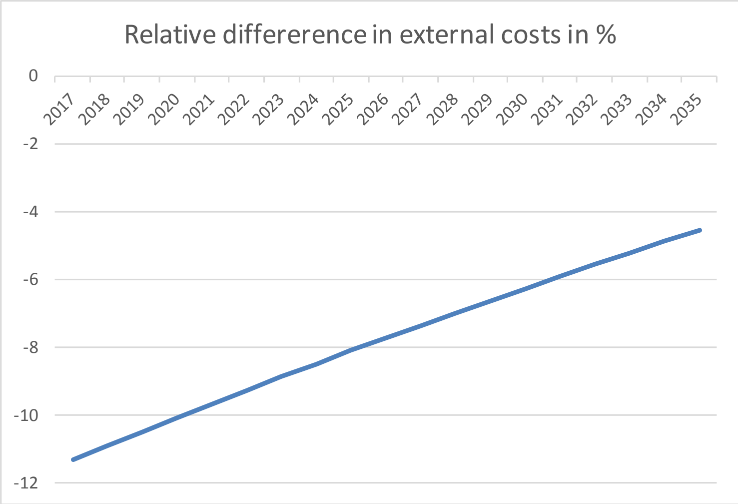

Figure 6: Relative difference in external costs between the scenario "without recycling" and the reference scenario

Again, the results greatly depend on the external unit cost of DEHP as shown in Figure 7 and the lack of knowledge on this critical parameter is problematic to assess the positive or negative effect of a "without recycling" policy vis-a -vis soft PVC in the coming decades.

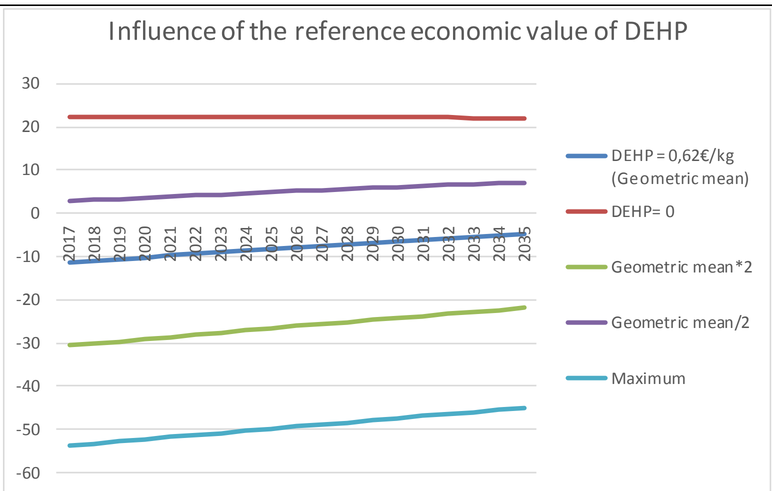

Figure 7: sensitivity test to the value of the external unit cost of DEHP ("without recycling" vs. "reference")

5. CONCLUSIONS AND OUTLOOK

We developed a model (with different options) to dynamically calculate changes in the overall external costs of providing a market with a material, taking into account the presence of hazardous chemical additives and their negative impact when the material is recycled. Originally developed for a uniform stock material, this model could, with significant developments in terms of computing resources, be adapted without methodological difficulty to the situation of a market consisting of a typology of different items, which flows mix when they are recycled.

We apply as an example the model to the illustrative case of the French market for flexible PVC and its hazardous phthalate additive DEHP. First, the model estimates that the total annual external costs of French soft PVC market are of an order of magnitude ranging slightly below the hundred millions of euros (30% of the annual value of flexible PVC market).

We show that increasing recycling (if the annual growth rate of 2% is increased to 3%) results initially in a increase of the total external costs. However, after a certain time (that varies depending on model parameters) there will be an overall positive and growing benefit to increase recycling rates. However, this time beyond which increased recycling becomes positive despite the prolongation of the presence of DEHP on the market is highly variable, depending on the model parameters, essentially on the values of external costs of DEHP.

Overall, differences remain anyway small in relative terms (order of 1%) of the cumulative total external costs over the period analyzed (20 years), if indeed possible extreme values for the health costs of DEHP are discarded.

We also simulated a fictional scenario of stopping recycling, which causes a significant increase in the medium term (from 2021) of the total external costs, also by an order of a magnitude that is very dependent of the unit value of health damage of DEHP.

Sensitivity tests confirm the importance of reducing the current uncertainty about the health impacts caused by DEHP, otherwise the choice between different recycling policy options cannot be analyzed meaningfully for the decision maker. This type of models and calculations is useful to show the temporal dynamics and long-term trends, in particular it suggests that recycling is always profitable in the long term.

The uncertainty of the external costs of DEHP would however be reduced and may allow a more operational use of the model to help in the decision, if, instead of an illustrative case for all the soft PVC, we worked on the well-defined articles, because then the concentrations of DEHP and the exposure conditions to articles and health impacts could be better clarified.

A more operational use of this framework in policy guidance for precise material involves a number of developments:

- first of all improving data on health impacts of additives in materials. We recall that beyond the case of DEHP, additives of a given material are numerous, and additives that will replace older banned additives are often even less well known.
- The development of a finer modeling framework, taking into account the typology of products with differentiated service lives and representation of the mixing of their flow during recycling. We show that such developments, without methodological difficulties, however, presuppose the implementation of more cumbersome methods of numerical computation as implemented for the simplified model presented here.

Finally, the development of such models would be useful to study the conditions for a sustainable circular economy. Indeed, introducing recycling, even intensively, in the economy, does not guarantee that external costs of using materials will remain within what is bearable for man and the environment. The deployment of models capable of quantitative projections in the very long term, could help to set recycling targets which comply with the long-term environmental and health constraints, similarly to what is done for the purposes of limiting greenhouse gas emissions in the area of climate change.

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7. TECHNICAL APPENDIX

Note: All numerical calculations were made with Microsoft Excel 2016. For some functions (Dawson function) that are necessary for some equations of the model, and which are not included in Microsoft Excel, a macro has been programed based on Dawson basic function algorithm provided in WH Press e al, 2007. "Numerical Recipes: the Art of Scientific Computing", Cambridge University Press.

7.1 CALCULATION OF THE MASS OF MATERIAL AND OF ADDITIVE ON THE MARKET

The material stock Q(t) is given by expression of the mass conservation for the material between t and t + dt:

$$\mathrm{Q(t+dt) = \ Q(t) + Q(}t\mathrm{).v(t).dt - Q(t).i(t).dt}$$

We consider that recycling is neutral in terms of mass balance between t and t + dt (an equivalent amount will be recycled at time t and returns to t + dt). We assume therefore no loss of material during the recycling. This simplifying assumption is a negligible source of uncertainty compared to other uncertainties on v(t) and i(t)[12].

We find a differential equation to calculate easily Q (t) according to the expressions chosen for functions i(t), r(t) and v(t), which are linear functions in the context of this study.

Q(t).C(t), which is the amount of additive present on the market at time t is obtained by expressing the additive mass balance between t and t + dt. The only variation between t and t + dt is related to the loss by incineration. We also assume that there is no loss nor transformation of additive during recycling[13].

$$\mathrm{Q(t+dt).C(t+dt) = \ Q(t).C(t) + Q(t).v(t).dt.0 - Q(t).i(t).dt.C(t)}$$

We find a differential equation which makes it easy to calculate Q (t) .C (t) according to the expressions chosen for the function i(t), r(t) and v(t), which are linear functions in this work.

7.2 CONSIDERATION OF A DELAY RELATED TO THE LIFETIME OF THE ARTICLE

The equations of the additive mass balance presented above are simplified compared to reality because during incineration at time t, a plastic object has an additive concentration C(t-T) (and not C(t)) where T is its lifetime on the market.

[12] Regarding modeling, the introduction of a loss during the recycling is equivalent to changing the incineration rate and would not result in significant changes in the model.

[13]Again, this can be easily introduced into the modeling framework and equivalent to the modification of incineration rates.

The mass balance expressed with this delay provides a delayed differential equation, that can be solved in several steps, each of duration T by providing simple initial conditions in terms of concentrations of additive during [-T, 0].

We tested the impact of this simplification using a delayed model instead of an instantaneous mixture model. We calculated and compared the two models for concentrations of the additive (in the case of the baseline that was used in the above scenarios comparisons).

We find that the relative difference between the two calculations of the concentration does not exceed 10% over time 0 to T (we take seven years for T in this example). Since the external cost of DEHP is proportional to both the economic reference value of DEHP and this concentration, the error caused by the simplification in the dilution model is very small compared to the uncertainty in the reference economic value DEHP. It is recalled that DEHP external cost can vary by a factor of 60 (compared to 10% after T years for concentration).

Note that these simplifications tends to overestimate the impact of DEHP and recycling.

7.3 GENERAL MODEL FOR N DIFFERENT TYPES OF ARTICLES

The mass balance of the formulation for the material is in this case, for articles of type j, is as follows:

$$\mathrm{Qj(t+dt)} = Qj(t) + \boldsymbol{v_j}(t)Qj(t)dt - \boldsymbol{i_j}(t)Qj(t)dt - \boldsymbol{r_j}(t)Qj(t)dt + \sum_{i=1}^{N} \boldsymbol{f_{i,j}}\boldsymbol{r_i}(t)Qi(t)dt$$

where :

- $i_j(t)$ $v_j(t)$ and $r_j(t)$ denote the incineration, production, and recycling rates of the material present in the articles of type j,
- $f_{i,j}$ denotes the proportion of the recycled flow of articles of type-i used to manufacture recycled articles of type j. For each j, the sum of all of these fractions is equal to one.

Thus, one obtains a differential linear system of order N that it is possible to solve (explicitly for a small number of items, otherwise numerically).

The mass balance of the additive for the articles of type j is written, taking into account the effect of the lifetime of the article which was mentioned in 7.2:

$$\begin{aligned}\mathrm{Qj(t+dt)}Cj(t+dt) &= Qj(t)Cj(t) + \boldsymbol{v_j}(t)Qj(t)Cvj(t)dt - \boldsymbol{i_j}(t)Qj(t)Cj(t-Tj)dt \\ &- \boldsymbol{r_j}(t)Qj(t)Cj(t-Tj)dt + \sum_{i=1}^{N} \boldsymbol{f_{i,j}}\boldsymbol{r_i}(t)Qi(t)Ci(t-Ti)dt\end{aligned}$$

Where :

The $Cv_j(t)$ variable is the concentration of the additive virgin material produced at time t (assuming the general case where the additive is not necessarily considered banned at t = 0, for example DEHP currently is not banned in strictly all articles made of soft PVC).

Tj is the lifetime of articles of type j

One thus obtains for each Q_jC_j function a linear differential system of order N with delays that can be resolved after the previous one on the Q_j (explicitly for a small number of articles and neglecting the delays, if not numerically). The two differential systems are independent if the Cv_j functions are all zero.

It is possible to introduce degradation kinetics additives. In the case of a first order kinetic order denoted k_j for articles of type j, this is equivalent to replacing in mass balance equations of the additive coefficients $i_j(t)$ by $i_j(t) + k_j$

The expressions of the external costs become in this framework:

For production, recycling and incineration processes,

$$\sum_{j=1}^{N} \int_0^t e^{-(d.u)}.(Ij.ij(u).\mathrm{Qj(u)} + Rj.rj(u).\mathrm{Qj(u)} + Pj.vj(u).\mathrm{Qj(u)})du$$

With I_j, R_j, and P_j respectively unit external costs of incineration, recycling and production for the article of type j.

For the additive,

$$\sum_{j=1}^{N} \left(\frac{ADDj}{\mathrm{d}}\right)(1 - e^{-d.Tj}) \int_0^t e^{-d.u} \sum_{i=1}^{N} \boldsymbol{f_{i,j} r_i}(u)Qi(u)Ci(u - Ti)\, du$$

With $_{ADDj}$ the unit external cost of the additive for articles of type j (since each type of articles can result in different exposures and therefore different impacts).