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TITLE

How much sorting is required for a circular low carbon aluminium economy?

AUTHORS

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KEYWORDS

Aluminum, Recycling, Optimization, Materials management, Circular economy, Industrial Ecology

HIGHLIGHTS

- Operations research is applied to material flow analysis and life cycle assessment
- Better sorting limits the inter-alloy contamination and downcycling of aluminium
- Improvement of sorting can reduce by 30% the GHG emissions of the aluminium industry
- Sorting becomes even more important with enhanced dismantling and collection rates

ABSTRACT

Aluminium recycling follows a downcycling dynamic where wrought alloys are transformed into cast alloys, accumulating tramp elements at every cycle. With the saturation of stocks of aluminium and the reduction of the demand for cast alloy due to electrification of transport, improvement in the recycling system must be made to avoid a surplus of unused recycled aluminium, reduce the overall environmental impacts of the industry, and move towards a circular economy. We aim to evaluate the potential environmental benefits of improving sorting efforts by combining operations research, prospective material flow analysis and life cycle assessment. An optimisation defines the optimal sorting to minimise climate change impacts according to different sorting efforts, dismantling conditions, and collection rates. Results show how the improvement of sorting can reduce by around 30% the GHG emissions of the industry, notably by reducing unused scrap generation and increasing the recycled content of the flows that supply the demand of aluminium. The best performance is achievable with four different sorting pathways. Further improvements occur with a better dismantling and an increase of collection rates, but it requires more sorting pathways. Results point to different closed-loop recycling initiatives that should be promoted in priority in specific sectors, like the building and construction sector and the aluminium cans industry. To implement a better material circularity, the mobilization of different stakeholders is needed. From a wider perspective, the article shows how operations research can be used to project a circular future in a specific industry.

1 INTRODUCTION

Circular economy aims to reduce primary material consumption, waste generation, and emissions while reducing environmental impacts (Korhonen, Honkasalo and Seppälä, 2018). Many approaches exist to achieve this objective, but recycling is the most studied of them (Kirchherr, Reike and Hekkert, 2017). Recycling reinserts material in the economy by substituting primary material and avoiding waste generation.

For the case of the aluminium industry, which has already a long history of recycling, efforts toward greater material circularity are motivated by important potential reductions in environmental impacts. In terms of greenhouse gas (GHG), the aluminum industry causes 1% of the overall emissions (Cullen and Allwood, 2013). The reduction potential of GHG emissions achievable through enhanced material circularity have been estimated for this industry in different regions and timeframes: 46% in Europe by 2050 (European Aluminium, 2020), 24% globally in 2050 (Material Economics, 2016). Nevertheless, few details are available on how the transformation must be done.

Aluminium is used in a wide range of forms and products like vehicles, industrial equipment, construction and packaging (Cullen and Allwood, 2013). It is not used in a pure form, but rather as an alloy in order to improve its mechanical properties. Major alloying elements include silicon (Si), iron (Fe), copper (Cu), manganese (Mn) and magnesium (Mg). There are two main families of alloys: wrought alloys and cast alloys, with the latter generally containing a larger percentages of alloying elements (The Aluminum Association, 2021). The whole life cycle of aluminium production, consumption and recycling depends substantially on international trade, making it a global commodity (Liu, Bangs and Müller, 2012; Milovanoff, Posen and MacLean, 2020).

While primary production is energy intensive because of the electrolysis process, the recycling process consumes 95% less energy, leading to lower environmental impacts (Liu and Müller, 2012; IAI, 2018). However, the presence of alloying elements in recycled aluminium due to inter-alloy contamination through the recycling processes represents an issue that limits its uses back into the industrial cycle. When different alloys are mixed, alloying elements composing the alloys are also mixed and the removal of those elements is thermodynamically challenging (Nakajima *et al.*, 2010). For this reason, the recycling system is currently operating in cascade, where a loss of quality occurs at every recycling cycle (Løvik, Modaresi and Müller, 2014). This dynamic is also called “downcycling”. Generally, wrought alloys are recycled into cast alloys, and primary aluminium is added to the recycled aluminium to maintain contaminant concentrations below tolerance limits (Cullen and Allwood, 2013; Løvik, Modaresi and Müller, 2014). This process, called sweetening, reduces the benefits of recycling. For example, the addition of 25% sweetener multiplies by 5 the embodied energy of recycled aluminium (Cullen and Allwood, 2013).

To this day, there are no commercially viable means to “upcycle” cast aluminium back into wrought aluminium. Over time, this one-way downcycling cascade leads to an ever-increasing supply of low-grade aluminium. Improvements in recycling processes are needed to ensure a better match between future recycled aluminium supply and demand. A better sorting would limit the inter-alloy contamination during the remelting process without requiring any novel metallurgical technological development to remove impurities (Gaustad, Olivetti and Kirchain, 2012). For example, if a specific aluminium alloy is collected and remelted separately, avoiding inter-alloy contamination, it could be recycled in a nearly-closed loop, virtually forever if not for losses in the recycling processes.

Understanding the dynamic of stocks and flows of aluminium within our society is key to identify pitfalls and advantages of the global recycling system. Material flow analysis (MFA) is a tool to systematically assess flows and stocks of materials within a system defined in space and time (Brunner and Rechberger, 2005). Several scholars have already applied prospective MFA to the aluminium sector and forecasted a future mismatch between sources of secondary aluminium and overall demand, warning that a surplus of low-grade recycled aluminium could occur (Hatayama *et al.*, 2009; Rombach, Modaresi and Müller, 2012; Bertram *et al.*, 2017). This is mainly due to the accumulation of tramp elements over recycling cycles (Liu, Bangs and Müller, 2011) and to a change in demand following the electrification of personal vehicles reducing the demand for component made of cast alloys, notably engine blocks (Hatayama *et al.*, 2012; Rombach, Modaresi and Müller, 2012; Modaresi, Løvik and Müller, 2014).

While a MFA typically tracks the flows and stocks of a specific material in a given system, it cannot by itself assess its environmental impacts, doesn't systematically cover alloying element, and can be geographically limited. Furthermore, MFAs that rely solely on fixed transfer coefficients present an unconstrained linear response when used for prospective modelling: the same faction is transferred to the same sector regardless of the amount or the capacity of this sector to accommodate this amount. Thus, MFA can identify the problem of contamination in the aluminium industry, its scope needs to be extended with a life-cycle perspective and complemented with sectoral constraints. The combination of MFA with operations research (OR), which is a set of mathematical techniques applied to the modeling, optimization, and analysis of a process, would allow us to explore the whole range of optimal solutions within the given constraints to improve the aluminium industry.

Operations research has already been used to assess improvement in aluminium flows management. Hatayama et al. (2009) applied a pinch flow analysis in order to assess the recycling potential of aluminium in Japan, the United States, Europe, and China showing that a reduction between 30% and 85% of primary aluminium consumption could be achieved in 2050. Zhu and Cooper (2019) developed a linear optimization model that analyzes the current and potential domestic U.S. recycling rates at different levels of collection from end-use scrap categories and determines the minimum quantity of virgin metal needed to satisfy new alloy demand. They have shown that only 70% of aluminium scrap could be recycled domestically (Zhu and Cooper, 2019)

While sorting is key in maximising aluminium recycling, no study has been done so far to evaluate the relationship between sorting intensity and primary material displacement. Aluminium sorting is also key towards a low impact industry, but a full transition to a circular business model is challenging due to the high number of alloys available (with more than 500 alloys registered (The Aluminum Association, 2021)), the labor cost of properly sorting these materials, and the difficulty to identify specific alloys (Gaustad, Olivetti and Kirchain, 2012). Improving the system from a low sorting and downcycling dynamics towards a better sorting system would require additional efforts not only in terms of human and financial resources, but also in new logistic activities. Those extra activities would consume additional energy and material leading to a hypothetical trade off between extra sorting effort and overall environmental impacts.

Here, we aim to assess how increases of the sorting effort can lead to a reduction of environmental impacts. Methodologically, we combine operations research, MFA, and life cycle assessment to quantify potential environmental benefits in terms of climate change impact for different numbers of sorting pathways. In other words, we strive to quantify what potential environmental gains that could theoretically be achieved if we were to sort the post-consumer aluminium scraps into 3, 4, 5, or *n* different recycling streams. Are there diminishing returns to an ever more refined scrap sorting? Are scraps from some sectors of the economy more compatible with each other and more amenable to a combined recycling stream without excessive loss of quality? We developed an optimal management model of aluminium scrap for a given number of recycling streams, to estimate the potential gains that could theoretically be achieved. This exploration is not an extrapolation of present practice, and therefore cannot serve to predict the future behavior of the industry but it rather guides the efforts towards a low carbon and circular future.

2 METHODS

2.1 GENERAL FRAMEWORK

To address the research objective, we developed an optimisation model called *Optimisation Number of Bins in Aluminium Recycling* (ONBAR) that focuses on the sorting of different aluminium products. The general framework of the optimisation model is shown in Figure 1. The system is divided into 3 main processes: the primary production, the in-use stock, and the recycling. This latter is sub-divided into sub-steps: sorting (a), remelting (b), and sweetening (c).

Figure 1

Figure 1: General methodology of ONBAR where flows to recycle split according to two transfer matrices (a and b) before the sweetening process (c).

2.1.1 Main aluminium flows

The main flows for the optimisation model are the demand of different aluminium alloys to fulfill in-use stock needs (f_d), and the end-of-life flows (f_{eol}) associated with the in-use stock dynamic. We used data from the PRASTOF model (Pedneault *et al.*, 2022), a dynamic MFA (dMFA) tool generating sector-specific scenarios for future demand and end-of-life flows of aluminium. Prospective scenarios are in line with the Shared Socioeconomic Pathways (SSP) framework (Riahi *et al.*, 2017) which develops possible evolution of our societies according to different levels of challenges to climate mitigation and adaptation. The scenarios are based on 5 narratives describing internally consistent evolutions of the societies according to demographic, economic, technological, social, governance and environmental factors (O’Neill *et al.*, 2017). The five different narratives are: SSP1-Sustainability, SSP2-Middle of the road, SSP3-Regional rivalry, SSP4-Inequality and SSP5-Fossil-fueled development (O'Neill *et al.*, 2017). The SSP framework has been developed by the climate change research community to facilitate the integrated analysis of future climate impacts, adaptation, and mitigation (Riahi *et al.*, 2017) and allows assessments of future resource management with greater comparability (Schandl *et al.*, 2020). The idea here is to test our optimization model of scrap sorting in different potential futures to test the robustness of our recommendations in the face of inherently unpredictable societal decisions.

Demand flows and end-of-life flows are subdivided into sectors, alloys, and alloying elements. The sectors covered are: Building and Construction (BC), Transport-automotive (Trans-Auto), Transport-freight (Trans-freight), Transport-other (Trans-oth), Machinery and Equipment (ME), Consumer durable (CD), Electrical Engineering-generation (EE-gen), Electrical Engineering-distribution (EE-dist), Packaging-cans (PC-cans) and Packaging-other (PC-other). The 16 alloys covered are: 1000 series, 2000 series, alloy 3003, alloy 3004, other 3000 series, 4000 series, 5052 alloy, 5182 alloy, other 5000 series, 6061 alloy, 6063 alloy, other 6000 alloys, 7000 series, 8000 series, cast alloys and die-cast alloys. Finally, the 10 elements covered are: Aluminium (Al), Silicon (Si), Iron (Fe), Copper (Cu), Manganese (Mn), Magnesium (Mg), Chromium (Cr), Nickel (Ni), Zinc (Zn) and Titanium (Ti). Input data of the model about demand and end-of-life flows are available in SI1-inflow and SI1-outflow.

2.1.2 Temporal and spatial scope

The time frame of the analysis is the period between 2015 and 2100 with a time resolution of the model of a 5-year. The time scope is in line with SSP scenarios, ensuring a compatibility of our framework with this modelling community. We used a global spatial scope because aluminium is a globally traded commodity (Milovanoff, Posen and MacLean, 2020).

2.1.3 Number of bins

The number of bins (n) represents the number of streams that the end-of-life aluminium flows (f_{tr}) can be sorted into (f_s) before the remelting to recycling. For example, with only one bin (n=1), all aluminium alloys are mixed prior the remelting into a single recycling stream, which would lead to a high contamination between alloys and an increase of sweetening needs. In contrast, a system that would rely on two bins (n=2), the end-of-life flows can be sorted into two different streams giving more possibilities to limit contamination and improve the remelting (See SI2.1.1 for figures showing this concept). By increasing the number of n, the different combinations of sorting and remelting grow exponentially but the solver will select the optimal values of the decision variable to reach the objective. The number of bins, representing a different level of sorting effort, is set as an exogenous parameter of the model. Thus, the optimisation is repeated for a number of bins varying from one to eight, which allow us to understand how the increase of sorting pathways can improve the system.

2.1.4 Ideal sorting case

To put in perspective the performance of the optimisation according to different numbers of streams, an ideal case where no contamination at all occurs is also modeled. This theoretical case would imply that each alloy from each sector is perfectly disassembled and sorted, avoiding any kind of contamination (See SI2-1.2 for a graphical representation). The ideal sorting case allows us to set the minimal possible impact and to compare it to the results of the optimisation according to a different levels of sorting effort, represented as different number of bins.

2.1.5 Decision variable

The decision variables of the system are the coefficient of the transfer matrices α and β. Alpha, the first transfer matrix ((a) in Figure 1), describes the sorting of the flows to be recycled (f_{tr}) into different bins to generate sorted flows (f_s). This represents the sorting behavior of people or industries treating the end-of-life flows. We assumed alpha coefficients to be constant over time.

The second transfer matrix ((b) in Figure 1) creates new alloys from sorted flows f_s generating a remelted flow (f_{rm}) and the residual unused scrap flow that can't be used to fulfill any demand ($f_{unused\ scrap}$). It represents the behavior of smelters combining the different commercially available sorted scrap streams to fulfill their demand. Finally, f_{rm} passes trough a sweetening process ((c) in Figure 1) where primary aluminium and alloying elements (f_{sw}) are added to the remelted flows (f_{rm}) to reach the appropriate composition of the alloys to generate the recycled flows f_r. In summary, while both primary flow (f_p) and recycled flow (f_r) can fulfill the demand (f_d), the solver selects optimal values of alphas and betas to meet the objectives within the constraints of the system.

2.1.6 Scope and boundaries

The current study mainly focuses on the post-consumption scrap and excludes fabrication scrap generated by fabrication and transformation yields. Those flows, despite their important volume, are traded in a market different than the post-consumer scrap (Bertram *et al.*, 2017). This type of scrap has high collection rates (Cullen and Allwood, 2013) and is generally reintroduced directly into the fabrication process limiting the contamination between the alloys.

This exclusion was also made by the model generating the aluminium flows (Pedneault *et al.*, 2022) used as input for the optimisation model. The mass balance of the present system is respected despite this exclusion while the demand flow represents all the aluminium physically embedded in the final consumption.

2.1.7 Open-source code

ONBAR was programmed with python using the pyomo package (Hart, Watson and Woodruff, 2011; Hart *et al.*, 2017). The solver ipopt (Waechter and Laird, 2021) has been used to solve the system. All the code and the input data are available on Github (https://github.com/jpedneault/ONBAR) and Zenodo (Pedneault, Majeau-Bettez and Margni, 2022) while the input data are also available in SI1.

2.2 OBJECTIVES AND CONSTRAINTS

The objective function aims to minimize the sum of overall GHG emissions of the system modelled as shown on equation (1). GHG emissions are associated with the production of primary material ($imp_{f_{tp}}$), the landfilling activities to dispose unused scrap (imp_{scrap}), the sorting ($imp_{sorting}$) and the recycling ($imp_{recycling}$) of the different alloys (equation (2), (3), (4) and (5)). As a baseline, optimisation towards the minimization of climate change indicator is performed.

In all equations, index *t* represents a specific year, index *i* a specific alloying element, index *j* a specific alloy, index *n* a specific bin, and index *p* a specific product. For example, $f_{d_{i,j,t}}$ means the demand flow of a specific alloying element, in a specific alloy at the year t.

As a sensitivity analysis, the optimisation is also conducted using a mineral resource scarcity indicator instead of the climate change indicator. As circular economy can be described as ”[a system] that is based on business models which replace the ‘end-of-life’ concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, […]” (Kirchherr, Reike and Hekkert, 2017), the material aspect cannot be ignored. Optimising towards a resource indicator will allow us to capture potential trade-off with climate change indicator.

The first constraints of the model aim to ensure the mass balance between the different processes of the system. The total primary production aluminium flow (f_{tp}) is the addition of the primary aluminium flow that supply the demand (f_p) and the sweetening flow (f_{sw}) (6)). The primary production that supplies the demand is the sum of different alloys calculated as the difference between the demand and the recycled flows (equation (7)). The equation (8) ensures the right composition of the recycled flow where $\theta_{i,j}$

represents the composition of alloying element *i* in the alloy *j* according to metallurgical standards (ASTM, 2011; The aluminum Association, 2015). The equation (9) quantify the sweetening need to get the required composition for the recycled flow. Equation (10) describes the output flow of the sorting matrices, where *p* is the different products that need to be sorted and *n* is the bin. The outflow of the second transfer matric, representing the remelting, is described by the equation (11). Equations (12) and (13) constraint the mass balance of the flows entering those two matrices.

Minimize:

$$\sum_t \left(imp_{f_{tp_t}} + imp_{scrap_t} + imp_{sorting_t} + imp_{recycling_t} \right) \quad (1)$$

Where

$$imp_{f_{tp_t}} = \sum_i \left(f_{tp_{i,t}} * imp_{primary_{i,t}} \right) \quad \forall\, t \quad (2)$$

$$imp_{scrap_t} = \sum_i f_{m_{unused\,scrap_{i,t}}} * imp_{scrap_t} \quad \forall\, t \quad (3)$$

$$imp_{sorting_t} = \sum_b f_{s_b} * imp_{sort} \quad \forall\, t \quad (4)$$

$$imp_{recycling_t} = \sum_b f_{s_{b,t}} * imp_{rec_t} \quad \forall\, t \quad (5)$$

Subject to:

$$f_{tp_{i,t}} = f_{p_{i,t}} + \sum_j f_{sw_{i,j,t}} \quad \forall\, i, t \quad (6)$$

$$f_{p_{i,t}} = \Sigma_j (f_{d_{i,j,t}} - f_{r_{i,j,t}}) \quad \forall\, i, \mathrm{t} \quad (7)$$

$$f_{r_{i,j,t}} = \theta_{i,j} * \sum_i f_{r_{i,j,t}} \quad \forall\, i, j, t \quad (8)$$

$$f_{r_{i,j,t}} = f_{rm_{\mathrm{i,j,t}}} + f_{sw_{ij,t}} \quad \forall\, i, j, t \quad (9)$$

$$f_{s_{i,n,t}} = \sum_p \left(f_{tr_{i,p,t}} * \alpha_{n,p} \right) \forall\, i, n, t \quad (10)$$

$$f_{m_{i,j,t}} = \sum_{n} \left(f_{s_{i,n,t}} * \beta_{j,n,t} \right) \quad \forall\, i, j, t \tag{11}$$

$$\sum_{n} \alpha_{n,p} = 1 \quad \forall\, p \tag{12}$$

$$\sum_{j} \beta_{j,n,t} = 1 \quad \forall\, n \tag{13}$$

2.3 ENVIRONMENTAL DATA

Environmental impact coefficients based on life cycle environmental data are needed to translate material flows into environmental impacts. The units of those coefficients are expressed in terms of impact per kilogram of material produced or treated according to the case. For example, some coefficients represent the environmental impacts per primary aluminium or specific alloying element produced whereas others are used to quantify the environmental impact of sorting, recycling or landfilling per kilogram of flow treated. The values of the coefficients are obtained from the life cycle inventory database ecoinvent (Wernet *et al.*, 2016) and the ReCiPe 2016 v1.13 life cycle impact assessment method (Huijbregts *et al.*, 2017).

The climate change indicator is used as a baseline minimization objective, while the minimization of the mineral resource scarcity mid-point indicator serves as a sensitivity analysis. All impact coefficients are assumed to be constant over time except for the primary aluminium production. The climate change impact coefficients for aluminium are based on plausible trajectories (pessimistic, optimistic, business-as-usual) for climate change mitigation and adaptation. This exploration of future impact has been done by Pedneault et al. (2021) according to the SSP framework (Riahi *et al.*, 2017) and integrating different consistent evolutions of the electricity mix and technological improvements. Those scenarios are also aligned with the one developed to characterise the main aluminium flows (see section 2.1.1).

Once the flows are optimised, impacts of the system are calculated for other mid-point indicators (Fossil depletion, Freshwater eutrophication, Human toxicity, Ionising radiation, Marine eutrophication, Water depletion, Ozone depletion, Particulate matter formation, Terrestrial acidification) to assess potential environmental co-benefits of improved sorting. See SI-impact and SI1-impact_mid_point for values of all environmental coefficients.

2.4 COLLECTION RATE

The collection rate allows us to calculate which proportion of f_{eol} goes to recycling with the rest going to landfill. Collection rate data by sector and regions are based on Müller et al. (2012) and are available in SI1-collection_rate. Constant values are assumed over time.

An optimisation with a hypothetical 100% collection rate is made as a sensitivity analysis in order to assess how the collection rate influences the results. This hypothetical analysis would allow us to see the potential environmental gains of increasing the collection rate.

2.5 DISMANTLING CASES

In addition to the collection rate, we assumed different dismantling cases that characterise f_{tr} prior to the first sorting of ONBAR. The first case is the one where dismantling does not occur at all and alloys from the same sector are mixed together before entering the recycling system. This implies a certain degree of contamination before the recycling because alloying elements and different alloys are mixed. In short: the origin of the scrap determines the sorting destination. From here, this case will be called *no dismantling*.

The second one represents the case where all pieces are dismantled and separated. It assumes that dismantling piece by piece is possible and that a piece is made of only one alloy. Then, all pieces made up of certain alloys, no matter their sector of origin, end up in a certain recycling stream. This would reflect a situation where sorting is not necessarily perfect (there are not necessarily as many recycling streams as there exists alloys in the economy), but the destination of individual pieces of scrap is at least based on their physical characteristics (Piorek, 2019) rather than their sector of origin. This case will be called *full dismantling*. A graphical representation of those two conditions is available in SI2-1.3.

3 RESULTS

Results of the optimisation toward the minimisation of the climate change indicator will be presented for three specific cases:

- ***SSP2-nd*** – Projections of flows following the middle-of-the-road narrative (SSP2) with the no dismantling case;
- ***SSP2-fd*** – Projections of flows following the SSP2 narrative with the full dismantling case;
- ***SSP2-fd-100cr*** – Projections of flows following the SSP2 narrative with the full dismantling case and a 100% collection rate.

At first, the minimization has been done for a different level of sorting efforts, with the number of recycling streams ranging between 1 to 8 bins, for the *SSP2-nd* case. This baseline represents the worst-case situation and will be compared to cases with an enhanced dismantling (*ssp2-fd*) and collection rates (*ssp2-fd-100cr*). In addition, all three cases would be compared to the "ideal" sorting case (see section 2.1.4).

3.1 NO DISMANTLING

Figure 2 shows the evolution of the total climate change impact over time to meet the evolution of the overall demand of aluminium as a function of the number of sorting streams for the *SSP2-nd* case. As a comparison, the hypothetical ideal sorting case where no cross-sector contamination at all occurs is also presented. Values used in this figure and subsequent figures are available in SI3. Model outcomes show that in 2015 a hypothetical condition where aluminium is sorted through one single pathway (one bin) would result in an annual emission of 1200 Mt of CO_2 eq., while it could be reduced to around 900 when increasing the sorting up to 8 bins. The gap in the results between the number of bins increases over time. In 2050, the total impact is projected to be 1500 Mt for 1 bin and 1050 Mt with 4 bins or more.

While the demand keeps increasing until 2090, the overall climate change impact peaks in 2075 before reducing. With no dismantling, no significant impact reduction is observed beyond 4 bins. According to this baseline situation, impacts are higher than the ideal sorting case and cannot be reached due to the contamination caused by the lack of dismantling. This limits the environmental performance of the system.

FIGURE 2

Figure 2: Overall climate change impact (from the production, sorting, landfilling and recycling) of aluminium system, no dismantling case, according to a different number of sorting pathways (bins) to meet the total aluminium demand for the middle-of-the-road (SSP2) projections (black dotted line following the right axis) (SSP2-nd). The black diamonds are the results according to the hypothetical ideal sorting where no contamination at all occurs.

The range of CC impacts between the number of sorting pathways is explained by differences in the production of primary aluminium and the generation of unused scrap surplus, both of which depend on the number of sorting pathways. Figure 3 (a) shows the evolution over time of the primary aluminium production needed to supply the demand according to a different number of sorting pathways for the *SSP2-nd* case. The black dotted line represents the associated overall aluminium demand. While the overall demand rises from 70 Mt/yr to 125 Mt/yr during the century, it would be theoretically possible to supply the overall aluminium demand with less than 60 Mt primary aluminium annually with an ideal sorting. More bins lead to a reduced total need for primary production because the recycled aluminium flows remain functional for a large number of applications due to lower cross-contamination of alloying elements, thereby displacing more primary production. With only one bin, an extreme case where no sorting is made at all, the contamination is very high and almost all demand must be supplied by primary production and sweetening. The recycled content rate of the flow supplying the demand is around only 3%. This rate can rise to almost 40% with the increase of sorting pathways. The range of total primary production between a low number of bins and a high number of bins tends to increase over time showing how the improvement of sorting gains importance in the future. However, no reduction of primary production is observed with more than four bins in the absence of dismantling.

Figure 3 (b) shows the generation of unused scrap over time according to the number of sorting pathways for the *SSP2-nd* case. It is compared to the magnitude of the flow to recycle represented by the black dotted line. Logically, the more sorting pathways we have, the less unused scrap is generated. Due to the contamination caused by the absence of dismantling, unused scrap is still generated even with a high number of bins.

FIGURE 3

Figure 3: Evolution of primary aluminium production (a) and the generation of unused aluminium scrap (b) over the century according to different numbers of sorting pathways (bins) for the SSP2-nd case. The black diamonds are the results according to a hypothetical ideal sorting where no contamination at all occurs.

Sensitivity analysis has been optimising the system to minimise the mineral resource scarcity indicator. Similar trends are observed, and results are presented in SI2-2.1 with additional explanations.

By calculating the environmental impacts according to other mid-points indicators, co-benefits are observed when increasing the number of bins (See-SI2.2.2 for a figure showing the improvements according to a different number of bins in 2050). This is explained by the fact that no matter the indicator, the production of primary aluminium is the main contributor for all indicators. An optimisation of the sorting leading to a reduction of total primary production would lead necessarily to a reduction of environmental impacts.

While previous results were shown for the middle-of-the-road (SSP2) material projections, a sensitivity analysis has been done evaluating the impacts for projections based on other socio-economic evolutions. Results are presented in SI2-2.3. Similar trends are observed meaning that no improvement is seen with 4 bins or more for the no-dismantling cases. Of course, the values of overall impacts are different due to the differences in demand of aluminium between the projections.

3.2 FULL DISMANTLING

In the previous section, the improvement achievable through improved sorting (by increasing the number of bins) is limited due to the contamination of the flows entering the recycling processes. Figure 4 shows the results of the *SSP2-fd* case meaning that non contaminated alloys (dismantled parts) enter the sorting process. The environmental performance equivalent to an ideal sorting can be reached with 6 bins or more even if the model covers 16 different alloys. With a 6 bins system, there is still some cascading and downcycling, but it is sufficiently limited that (with the baseline collection rate, and increasing overall demand), almost no alloy is produced in excess of its demand over the investigated period.

Impacts with full dismantling are lower than the ones with no dismantling showing an additional reduction of 15% with 4 bins and up to 30% for a larger number of bins. Once again, the range of impact between the number of bins increases over time. See SI2-2.4 for the total primary production and scrap generation graphs.

FIGURE 4

Figure 4: Total impact of the full dismantling case according to a different number of sorting pathways (bins) to meet the total aluminium demand for the middle-of-the-road (SSP2) projections (black dotted line following the right axis) (SSP2-fd). Grey dots are the results from the no dismantling case with 4 bins in order to compare results. The black diamonds are the results according to an ideal sorting where no contamination at all occurs.

3.3 IMPROVING COLLECTION RATE

The results of the SSP2-fd-100cr case are presented on Figure 5. A 100% collection rate would reduce drasticaly the overall impacts even with a limited number of 2-3 bins. For comparison with previous figures, the grey dots represent the results from SSP2-nd at 4 bins and the grey crosses from the SSP2-fd case with 6 bins and a baseline collection rate. The baseline collection rates, that depend on the sector, vary between 11% (PC-Other) and 88% (BC).

This situation leads to an absolute decoupling of the CC indicator, meaning that absolute impacts are reduced despite the increase in demand. This is explained by the reduction of total primary production due to an increase of recycled flows capable to satisfy the increasing overall aluminium demand (See SI2-2.5 for the evolution of the total primary production and scrap generation). In comparison with the baseline collection rate, for an equivalent number of bins, more unused scrap is generated with a perfect collection rate because recycling flows are bigger, limiting the difference between the demand and the end-of-life flow and the possibilities of downcycling. However, due to the relatively low environmental impact of landfilling scrap (0.04 kg CO_2 eq / kg) in comparison to primary production of aluminium (≈ 15 kg CO_2 eq / kg), the overall impacts are reduced when the collection rate increases even if it generates more unused scrap.

In comparison with the baseline collection rate, the range of impacts between the number of bins is even higher, showing how the sorting becomes more and more important if the collection rates increase.

FIGURE 5

Figure 5: Total impact of the full dismantling case according to a different number of bins with a hypothetical perfect collection rate (SSP2-fd-100cr). Grey dots are the results from the no dismantling case (SSP2-nd) with 4 bins and the gray crosses are the

results from the full dismantling case (SSP2-fd) with 6 bins in order to compare results. The black diamonds represent the results from the ideal sorting case still with a 100% collection rate.

Relative impact in kg CO_2 /kg aluminium demand is calculated over time and for SSP2-nd, SSP2-fd and SSP2-fd-100cr cases according to a different number of bins. The rates have been calculated by dividing the overall CC impact by the overall demand. Tables with those relative impacts are available in SI3-relative_impacts.

3.4 SORTING

To understand exactly how the different flows are mixed and then recycled into new alloys, values of alphas and betas are represented with Sankey diagrams according to different dismantling and sorting cases. The values of those coefficient are the results of the decision variable of the optimisation model. Figure 6 shows the recycling flows optimised for the year 2050 and four bins. In addition to this figure, it is possible to generate any Sankey diagram for different number of bins and conditions with this interactive online tool: Binder_Sankey_ONBAR (See SI2-2.6 for specific indications on how to obtain other diagrams).

Figure 6 (a) shows the *SSP2-nd* case with 4 recycling streams. Alloys from building and construction are sorted into one bin and recycled into 6063 alloys (the main alloy in the BC sector) and 5182 alloys used to produce cans. The packaging-cans are also sorted into their own bin and lead to the production of 5182 alloy and other 6000 series. The alloys from automotive transport are sorted into a bin that generates all the unused scrap that cannot supply the demand. Packaging sectors are mixed to generate 6000 series and 5182 alloys. The fourth bin receives aluminium from other sectors to downcycle it into cast alloy.

Figure 6 (b) shows the *SSP2-fd* case. We observed that less unused scrap is generated in comparison with the no dismantling case. The input alloys of bin 2 are mainly the alloy 6063 that comes from the building construction sector in addition to other purer alloys like 1000 and 8000 series producing new 6063 alloys. Bin 3 generated mainly the alloy 5182 that is used for can production. Bin 1 generates 6000 alloys mainly from the 3000 and 6000 series. Finally, bin number 4 combines cast and die-cast alloy to generate the unused scrap and a little part of cast and die-cast recycled alloys.

Figure 6 (c) shows the *SSP2-fd100cr* case. Bins 1, 2 and 3 produce mainly alloy 3004, 6063 and 5000 respectively while the fourth bin produces the cast alloy the unused scrap.

FIGURE 6

Figure 6: Sankey diagrams of the specific year 2050 and 4 bins with global values. (a) shows the SSP2-nd case (b) shows the SSP2-fd case (c) shows the SSP2-fd-100cr case. The sectors covered are: Building and Construction (BC), Transport-automotive (Trans-Auto), Transport-freight (Trans-freight), Transport-other (Trans-oth), Machinery and equipment (ME), consumer durable (CD), Electrical Engineering-generation (EE-gen), Electrical Engineering-distribution (EE-dist), Packaging-cans (PC-cans) and Packaging-other (PC-other)

This analysis highlights the relevance of going beyond a simple cast / wrought separation to minimise climate change impact and therefore transform the aluminium industry towards a more circular value chain by an increase of sorting, dismantling and collection rate.

4 DISCUSSION

4.1 COMPARISON WITH PREVIOUS STUDY AND LIMITATIONS

ONBAR is a theoretical optimisation model that can inform on the trends of the recycling system in the aluminium value chain. The model allows us to explore the relationship recycling parameters (number of sorting pathways, collection rates and dismantling condition) and the environmental impacts of an industry. The integration of life cycle assessment and material flow analysis data into an optimisation model show how circularity can be studied with a holistic and systemic perspective. Of course, a model is a simplified representation of a more complex reality, but comparison with existing literature can evaluate the relevance of the model.

According to the International Aluminium Institute (IAI), the reported GHG emission of the aluminium sector, excluding internal scrap remelting and semis production, were 956 Mt in 2015 (2021). For the same year, ONBAR calculated 943 Mt CO_2 eq. for a sorting pathway of 2 bins. Vatne (2019) estimated the total impact of the primary production at 1000 Mt CO_2 eq. in 2018, which is right between the calculated impact of our baseline scenario for 1 and 2 bins.

In addition, a comparison with AluCycle from IAI (2020) can be made even if the boundaries of their system are larger than ours because they take into account production and transformation yields. Their recycled content (the division of their final product demand and the old scrap flow that is recycled), is 23% in 2015, 33.3% in 2030 and 42% in 2050. In our results, similar rates are obtained for a system with a number of 2 bins but limited at around 35% for a baseline scenario with no dismantling. It is plausible that the global recycling system might currently indeed present an overall behaviour somewhere between no sorting (1 bin) and sorting between wrought and cast aluminium (2 bins), in different regions of the world. However, a comparison between our results and Alu-cycle projections can only be made with relative indicators (like recycled content) because their demand and the end-of-life flows are different from ours.

ONBAR also forecasts the generation of unused scrap in the future if the sorting is insufficient. Hatayama et al. (2009) obtained similar conclusions by optimizing recycled flows between 4 world regions and forecasted that 12.4 Mt of recycled flow «would not be recycled because of the excess presence of alloying elements» by 2050. We obtained, with a different goal and method, a value of 14.3 Mt in 2050 with 4 bins or more for our no dismantling case.

Even if our model is in range with existing literature on the aluminium industry, some limitations occur. Results of the optimisation are greatly dependent of the input data: the future demand and end-of-life flows. While projections of aluminium flows with an alloys and alloying element perspective are rather rare, we used what we judged most up to data available (Pedneault *et al.*, 2022). Sensitivity analysis on different projections of aluminium flows based on socioeconomic evolutions of the society in line with the SSP framework (Riahi *et al.*, 2017) was done in order to test the robustness of the model. In the case where new and more accurate projections are published, ONBAR could still be used with those new data to give information on how to improve the recycling system.

The flows used are split into 10 sectors, 16 alloys and 10 alloying elements but the optimisation model could deal with a bigger disaggregation of those flows. Considering more alloys and more alloying elements in the flows could lead to potentially more sorting needs, but we judge that it wouldn’t change too much the overall performance of the system because alloys for the same family have somehow similar composition with only small variations. For example, further disaggregation of the 6000 series wouldn’t change the recommendation of not mixing the 6000 series with other families.

As only sweetening has been modeled by ONBAR, it would be possible to improve the model by adding purification technology capable of removing some alloying elements. The integration of those processes would require some environmental data like the CO_2 eq. / kg of alloying element removed with a life cycle perspective. Zhang et al. (2011) reviewed different techniques for removal of impurity elements from aluminium processes with a thermodynamic perspective. The integration of purification technology in the optimisation could lead to a reduction of the overall impacts of the industry. It could also potentially reduce the sorting needs to reach the minimum impact with fewer bins if the environmental effort of removing alloying elements is lower than the logistic of sorting aluminium scrap in more bins. However, except for Mg and Zn, alloying elements are very difficult to remove from aluminium due to its low melting point and its strong affinity for oxygen (Nakajima *et al.*, 2010). Purification techniques could not, by themselves, fix all the contamination problems of recycling, highlighting the needs for a suitable sorting.

While the model focuses on the aluminium flows and its alloying elements, contamination with other base metals (e.g., iron) that can contaminate a recycling stream without being initially an alloying element, was excluded from the scope of this study. This would theoretically increase the dilution needs and reduce the environmental performance of the overall system. Different parameters can influence the contamination like the joining techniques (Soo *et al.*, 2018) and choice of sorting equipment (Gaustad, Olivetti and Kirchain, 2012). The theoretical optimisation model also excludes the possibility of false detection during the sorting process and assumes no limitation to sorting other than lack of dismantling (in -nd scenario) and a limited number of sorting streams. This exclusion under evaluates the dilution needs to overcome this contamination. It represents an upper-bound of the performance and climate mitigation gains that could be achieved (in a given system and a given sorting strategy). Future studies could integrate those type of contamination and evaluate the consequences on the environmental performances of the system.

The long temporal scope of the study generates uncertainties, but it is important to remember that scenarios used to obtain aluminium flows (Pedneault *et al.*, 2022) do not aim to predict the future but rather to describes possible and consistent future of the aluminium industry. The sensitivity analysis testing the optimisation model according to different aluminium flows in line with different SSPs shows that trends and recommendations are similar no matter the socioeconomic evolution.

Despite the limitations and the inherent uncertainties of this theoretical optimisation model, it allows us to understand the interconnection between environmental performance of the aluminium system, the post-consumption sorting intensity and collection rates. From this understanding and the results obtained, it can be greatly useful in setting performance targets and directing scrap-sorting efforts toward the options with the greatest potential benefits.

4.2 TOWARDS A CIRCULAR ALUMINIUM INDUSTRY

The results generated by the optimisation model have shown how the transformation of the aluminium industry towards circularity should be driven by 4 different levers: the improvement of sorting, dismantling, collection rates, and the valorisation of the unused scrap. ONBAR has highlighted how an appropriate sorting becomes more and more important over time when stocks get saturated, with a better dismantling and a higher collection rate. Those four levers are interconnected and must be all improved to achieve a better circularity.

ONBAR has allowed us to identify the sectors and alloys where closed-loop recycling should be implemented in priority: aluminium cans and building and construction. While closed-loop recycling of aluminium is already in place in several countries with a system of deposit on single use containers (Detzel and Mönckert, 2009; Dace, Pakere and Blumberga, 2013), those initiatives should be more widespread. For the building and construction sector, to our best knowledge, no system is in place to ensure closed-loop recycling. A such transformation should be implemented but would need the participation of different stakeholders from the aluminium industry.

Circular economy might benefit from the development of industry 4.0 (Rosa *et al.*, 2020; Gupta, Kumar and Wasan, 2021). For instance, the implementation of a traceability system would enhance sorting and dismantling of aluminium at its end-of-life. Similarly, detection equipment capable of readily identifying aluminium alloys (Gaustad, Olivetti and Kirchain, 2012; Piorek, 2019) could significantly improve sorting in recycling facilities or during the demolition phase of buildings.

The increase of collection rate is another lever to reduce environmental impacts of the industry. While some sectors like transport and construction have collection rates higher than 80%, other sectors like consumers durable, packaging and machinery, and equipment are still far from those rates (Liu, Bangs and Müller, 2012). Targeted efforts should be done in order to improve collection rates, increase the recycled flows and ultimately reduce the environmental impacts of the aluminium industry.

While a solution that fits for all sector doesn't exist, recommendations for improving the collection rate are manifold: design of products that allow for an easier dismantling, education to raise awareness of potential benefits of recycling in industry, economic incentives, development of more efficient sorting infrastructures, and improvement of sorting technologies (Graedel *et al.*, 2011). However, a 100% collection rate, as tested by the model, is unrealistic and probably unwanted. As formulated by Schmidt (2021): «[…] there is an optimum for the recycling rate that is well below 100 %. This is due to the dissipation of elements in materials and the increasing energy demand at low concentrations. » Further research could explore this optimal recycling rate specifically for the aluminium industry.

The issue of unused scrap generated should also be addressed. While cast alloys are responsible for most of the surplus, the improvement of casting technologies enhancing properties of cast alloys could help reducing this waste. By improving the casting process and better controlling the microstructure of aluminium alloys (Puga, 2020), cast alloys could be used for new applications that would lead to a greater demand of cast alloys limiting the surplus problem.

Alternative valorisation could also be pursued. For example, the metal combustion is a novel concept of energy vector in which metal fuels are burned with air in a combustor to provide clean, high heat (Bergthorson *et al.*, 2015). Aluminium production is energy intensive, and a part of this energy can be released when the substance is oxidised. The calorific value of aluminium oxidation is about 31 MJ/kg with a maximum cycle efficiency of aluminium-based energy storage of 43% (Shkolnikov, Zhuk and Vlaskin, 2011). While the energy potential is quite limited in comparison to total energy consumption, the unused scrap of aluminium could participate as a buffer in any electricity generating technology with zero self-discharge (Shkolnikov, Zhuk and Vlaskin, 2011).

In a broader perspective, with the increase of recycled content in the supply of aluminium demand, serious considerations for the development of new recycling-friendly alloys should be given. According to Das (2006), a recycling-friendly alloy requires: « composition with (a) relatively broad specification limits on major alloying elements such as Cu and Mg plus (b) more tolerant (i.e., higher) limits on Fe, Si, and other impurities, without significant restriction on performance characteristics for many applications». A larger market share of recycling-friendly alloys would reduce the sorting needs, facilitate the substitution of primary with recycled aluminium and contribute to reduce the overall impact of the industry. Of course, changes towards recycling-friendly alloys cannot be done to the detriment of basic characteristics of the alloy and its type of use. Identification of potential overspecifications for different uses should be done first to identify sectors or products where the integration of recycling-friendly alloys should be done.

4.3 CIRCULAR ECONOMY, RECYCLING AND BEYOND

While circular economy has no international recognised definition (Kirchherr, Reike and Hekkert, 2017), a recurring goal of the many definitions is to reduce the impacts of the system. Researchers must ensure that the increase of circularity leads to a reduction of environmental footprint knowing that trade-off between circularity and environmental impacts may occur (Lonca *et al.*, 2018). Due to dismantling and sorting challenges, a specific circular initiative could lead to counter-productive gains within the system. As cited by Schmidt (2021): «The ‘’closing the loop’’ metaphor of Circular Economy is therefore inappropriate in its stricter meaning. It is rather about optimizing the overall system […] ». Increasing recycling should not be the absolute priority but should be considered as a means to improve the system according to its specific barriers and constraints. Common recycling indicators, like recycled content or collection rate, largely fail to capture those system dynamics and are therefore incomplete and shouldn’t be interpreted as circular indicator. Indicators based on the general performance of the system, integrating a life cycle thinking, should be favored. To avoid geographic impact shifting, a macro scale should also be favored. Typical circular economy indicators focussing on the circularity, like the Material Circularity Indicator (Ellen MacArthur Foundation, 2022) should be complemented with LCA indicators to ensure that improvements are made at a system perspective. See Moraga et al. (2019) for a classification framework of circular economy indicators. Our model has shown that for the aluminium industry, no trade-off occurs; improvements on sorting, dismantling, and collecting can lead to a reduction of impacts and simultaneously a better circularity.

ONBAR has highlighted how benefits of recycling can only be fully observed with specific sorting and dismantling conditions. In a sub-optimal solution, unused scrap can be generated, and recycled material wouldn’t directly substitute primary material limiting environmental benefits of recycling. This dynamic contradicts the 1:1 rate substitution used in life cycle assessment to model recycling. Different parameters, for instance quality of recycled material and market dynamics, should be take into account when assessing the environmental benefits of recycling (Vadenbo, Hellweg and Astrup, 2017; Zink, Geyer and Startz, 2017; Viau *et al.*, 2020).

4.4 CONCLUSION

In this article, we developed an optimisation model combining material flow analysis and life cycle assessment to determine how the improvement of the sorting of aluminium can reduce the environmental impacts of the industry. The optimisation is made according to different sorting efforts, socioeconomical evolutions of the societies, dismantling conditions and covering the 2015 to 2100 period.

While inter-alloys contamination limits the benefits of recycling, the model has shown that an optimal sorting could reduce the primary aluminium production by 30% in 2050. This leads to an annual reduction of greenhouse gas emissions of 30% in comparison to a no sorting scenario. The sorting needs become more and more important as the accumulation of aluminium stock in the Technosphere slows down and the end-of-life flows of aluminium to be recycled increase over time. Enhanced dismantling leads to bigger reduction of environmental impact (45% of reduction by 2050 in comparison to the no sorting scenario) by limiting contamination prior the recycling itself. An increase of collection rate could even lead to a decoupling between the demand of aluminium and the environmental impacts of the industry when combined with appropriate sorting and dismantling. We also identified different closed-loop recycling that should be promoted in priority in specific sectors, like the building and construction and the aluminium cans.

Results have shown how a circular transformation of the aluminium industry has clear co-benefits on its decarbonisation and other environmental indicators.

Additional works could be done in order to overcome some existing limitations by adding transformation yields, purification techniques, contamination with other metals and imperfect sorting in the scope of the model. It would also be possible to simulate the consequences on the system of using more recycling-friendly aluminium alloys (Das, 2006) or even adapt the optimisation model to other materials with their own specific constraints.

Finally, this article fits into the broader trend of integrating modelling tools (LCA, MFA, OR) to guide circular economy initiatives. While this article covers the recycling process, the way to implement circular economy are multiple. Additional work could evaluate feasibility and quantify potential gains of other circular initiatives like reuse, refurbish, remanufacture and material efficiency.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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DATA AVAILABILITY STATEMENT

The input data that supports the findings of this study are available in the supporting information of this article. The code used for calculation is available on GitHub https://github.com/jpedneault/ONBAR, commit f*or submission)* and on Zenodo (Pedneault, Majeau-Bettez and Margni, 2022).

SUMMARY OF SUPPORTING INFORMATION

Supporting Information

Supporting information is linked to this article on the JIE website: https://jie.yale.edu/

Supporting Information S1: This Supporting Information (SI1_input_data) provides all input data of the ONBAR model: inflows, outflows, impact coefficients, composition of alloying element for each alloy and collection rate.

Supporting Information SI2: This supporting information (SI2) provides more information on methods and results from sensitivity analysis.

Supporting Information SI3: This Supporting Information (S3_data_figures) provides data from Figure 2, 3, 4, 5 of the article. It also provides data from our figures SI4, SI5, SI6, SI7 and SI8 available in Supporting information 2.

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CAPTIONS

Figure 1: General methodology of ONBAR where flows to recycle split according to two transfer matrices (a and b) before the sweetening process (c).

Figure 2: Overall climate change impact (from the production, sorting, landfilling and recycling) of aluminium system, no dismantling case, according to a different number of sorting pathways (bins) to meet the total aluminium demand for the middle-of-the-road (SSP2) projections (black dotted line following the right axis) (SSP2-nd). The black diamonds are the results according to a hypothetical ideal sorting where no contamination at all occurs.

Figure 3: Evolution of primary aluminium production (a) and the generation of unused aluminium scrap (b) over the century according to different numbers of sorting pathways (bins) for the SSP2-nd case. The black diamonds are the results according to a hypothetical ideal sorting where no contamination at all occurs.

Figure 4: Total impact of the full dismantling case according to a different number of sorting pathways (bins) to meet the total aluminium demand for the middle-of-the-road (SSP2) projections (black dotted line following the right axis) (SSP2-fd). Grey dots are the results from the no dismantling case with 4 bins in order to compare results. The black diamonds are the results according to an ideal sorting where no contamination at all occurs.

Figure 5: Total impact of the full dismantling case according to a different number of bins with a hypothetical perfect collection rate (SSP2-fd-100cr). Grey dots are the results from the no dismantling case (SSP2-nd) with 4 bins and the gray crosses are the

results from the full dismantling case (SSP2-fd) with 6 bins in order to compare results. The black diamonds represent the results from the ideal sorting case still with a 100% collection rate.

Figure 6: Sankey diagrams of the specific year 2050 and 4 bins with global values. (a) shows the SSP2-nd case (b) shows the SSP2-fd case (c) shows the SSP2-fd-100cr case. The sectors covered are: Building and Construction (BC), Transport-automotive (Trans-Auto), Transport-freight (Trans-freight), Transport-other (Trans-oth), Machinery and equipment (ME), consumer durable (CD), Electrical Engineering-generation (EE-gen), Electrical Engineering-distribution (EE-dist), Packaging-cans (PC-cans) and Packaging-other (PC-other)