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Barriers and solutions for closed-loop aluminium beverage can recycling

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Submission date: June 2013
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Acknowledgments

This thesis was completed in June 2013 to achieve the master degree in Industrial Ecology at the Norwegian University of Science and Technology (NTNU). I would like to express my gratitude to my supervisors Daniel Müller and Amund Løvik, who patiently guided me throughout this process during one semester of work.

I want to thank all the new friends I made in Norway and to all in the Industrial Ecology program. I want to thank Zuzana, Gonzalo and my friends in Moholt, with whom I spent great moments and made my stay in Trondheim unforgettable. Finally thanks to my parents, Ernesto and Emiko for their support in this adventure, and to my siblings Maby, Valeria and Marco.

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Trondheim, June 2013

Abstract

The aluminium can is the second largest end-use application in the USA. The aluminium sector in the USA has the target to increase the use of aluminium can scrap, in order to increase the economical and environmental benefits of recycling. The objective of this thesis is to identify the most important barriers to closed-loop recycling of aluminium beverage cans in the USA, and explore potential solutions. The research was conducted using the material flow analysis framework, creating a static model for the secondary aluminium production for cans, and a detailed dynamic model for beverage can recycling, in order to track various chemical elements through the cycle and including all relevant entry paths of contamination to the system. The dynamic model was developed to quantify the accumulation of alloying elements after each recycling loop in a can-to-can system, in order to predict the maximum recycling rate achievable.

The results show that the main barrier to reach the 75% can recycling rate target set by the aluminium industry in the USA is the low recovery of UBCs after the use phase, where almost 50% of the UBCs are lost to landfills or incineration facilities. The results also shows that the surplus of alloying elements and entry of impurities will be a limiting factor in the recyclability of cans in the future, if the recycling rate increases and a close loop can-to-can system is achieved, owing to the system's sensitivity to the entry of impurities. Without a better UBCs recovery and supply chain, further technological development for reprocessing aluminium cans, and improvement of production yields, it will not be possible to reach 100% recycling rate.

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1. Introduction

1.1 Motivation and background

The aluminium can sector has the objective to gradually increase the content of recycled aluminium in the production of new aluminium beverage cans, in a way to reduce costs, improve the environmental performance and benchmark the recyclability of aluminium cans. In order to increase the recycled content, more post-consumer scrap (old scrap) has to be used in the manufacture of a new product. Aluminium is the third most abundant chemical element on the earth crust (around 8%) and the second most commonly used metal in the world (Buffington, 2012), owing to its physical and mechanical properties such as light weight, corrosion resistance, manufacturability, non-toxicity and heat conductivity (Yoshida & Baba, 2010). Compared to other metals, aluminium production is on its early stages, and the penetration of the use of this metal in the society is growing rapidly.

Because aluminium is not found in its useful state in the nature, it must be processed from bauxite, which is the main aluminium ore source. The transformation of bauxite into aluminium generates a large amount of waste and has low energy efficiency. As a matter of fact, 4 to 6 tonnes of bauxite are needed to obtain 1 tonne of primary aluminium. Electricity consumption for the production of primary (virgin) aluminium is larger compared to other metals, such as steel. In fact, the global energy demand for primary aluminium production is estimated to be around 3% of world's total energy consumption (Buffington, 2012). Thus, around 10 to 12 tonnes of CO2 may be released per ton of primary aluminium produced, being the electrolytic process (reduction of aluminium oxide to obtain aluminium) the largest contributor with around 75% of the total CO2 emissions (Choate & Green, 2004; PE Americas, 2010). Additional outputs of environmental concern due to primary aluminium production are the red mud, which is waste generated during the refining process (transformation of the bauxite ore into alumina/aluminium oxide), normally disposed in landfills; and perfluorocarbons (PFCs), generated during the electrolytic process (Menzie *et al.*, 2010). PFCs trap heat in the atmosphere, contributing to global warming (Marks *et al.* 2000). The red mud is slurry that contains iron oxides (giving it its distinctive red color), Si, Al, Ca, Ti, and a wide number of organic compounds (Red mud project, 2005).

On the other hand the production of secondary aluminium from scrap aluminium sources, consumes only around 6% of the total energy required to produce primary aluminium (186 MJ/kg for primary against 10-20 MJ/kg for secondary) (Gaustad *et al.*, 2012), and representing only 4-5% of the green house gas (GHG) emissions (Velasco & Nino, 2011). The use of aluminium scrap may also forestall the depletion of aluminium ore (Gaustad *et al.*, 2011). Moreover, secondary aluminium production requires only 10% of the capital cost needed for the production of primary aluminium, to a certain extent owing to a simpler supply chain (Buffington, 2012).

Aluminium is almost always used in an alloyed form. Aluminium applications are manufactured from diverse alloy series. Each of the series has a different main alloy, which modifies the aluminium properties such as softness, reactivity and formability (The Aluminum Association, 2011). The three main series used for packaging are the 3000-series

(Manganese as main alloy), the 5000-series (Magnesium as main alloy) and the 1000-series (high purity aluminium, with less than 1 wt % of total of alloying elements) (Greenblue Institute, 2011). The 1000-series has superior corrosion resistance and high electrical conductivity. The 3000-series has improved strain hardening without appreciably reduction of ductility or loss of corrosion resistance. The 3000-series retains strength at high temperatures. The 5000-series shows increased strength and improved hardening without considerable decrease of ductility. It has the highest strength of non-heatable aluminium alloy (ESAB, 2013). Figure 1 visualizes the relationship between alloys and the different aluminium applications in the industry.

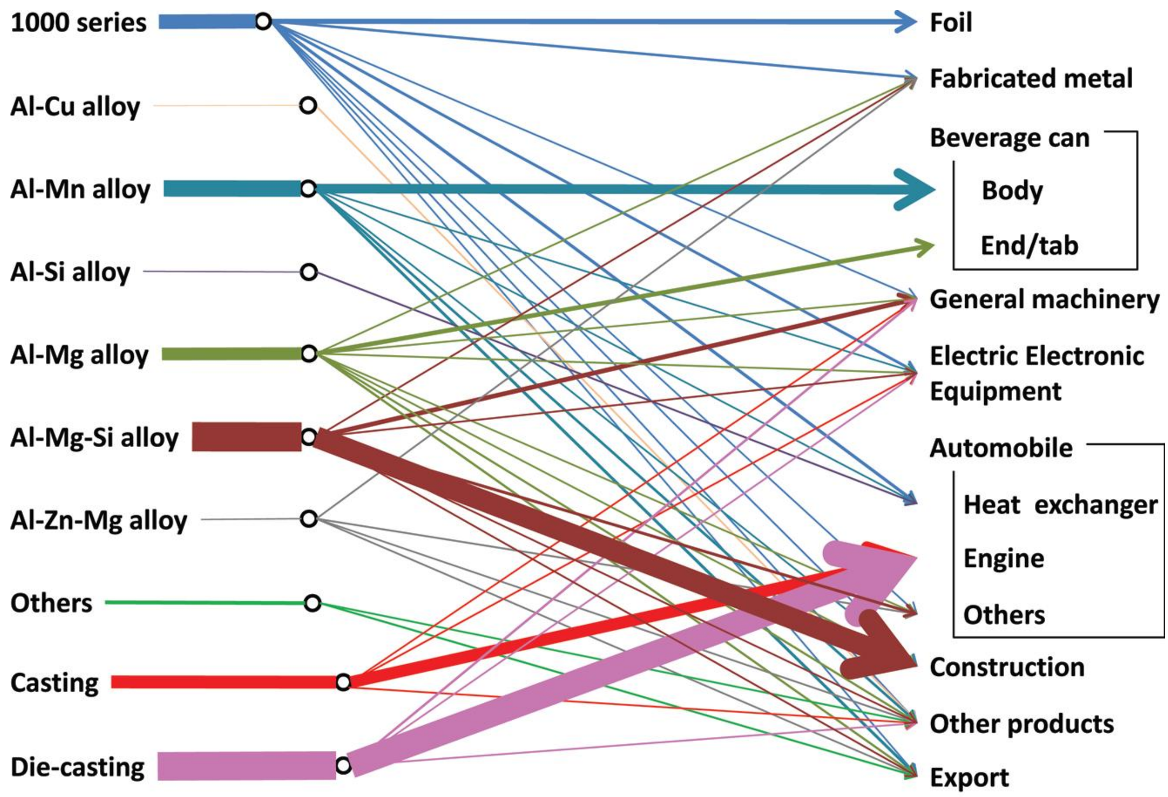

Figure 1: Demand of aluminium alloys by industrial sector (Nakajima *et al.*, 2010)

As seen in figure 1, Al-Mn alloy (3000-series) is used for the body, while Al-Mg alloy (5000-series) is used for the lid (end) and tab. The lid and tab may also differ in alloying elements concentrations (different percentages of alloying elements). When the used beverage cans (UBCs) are recycled, the alloying elements from the bodies are melted together with the alloying elements from the lid. Thus, the concentration of alloying elements in the recycled aluminium will be different from the concentration of both body and lid. The concentration of Si, Fe, Cu, Mn, are higher in the body than in the lid. Conversely, the concentration of Ti and Mg are higher in the lid than in the body. The recycled UBCs are nowadays remelted to use in the body production. Hence, higher concentration of Ti and Mg is expected in the new body stock. This implies that not only the amount of aluminium, but also the concentrations of alloying elements influence the maximum recycling rate reachable (Hatayama *et al.*, 2007). Both the deficit and the excess of alloying elements may affect the aluminium properties, and thereby precise control over the alloying elements during the remelting process is necessary. Inclusions of impurities in the body may cause perforations and tear-offs during the can manufacturing process (Doutre, 2011).

Impurities may be introduced into the system during the use phase or through the scrap dealers. For example organic substances or metals may be placed inside the UBCs and end up in the remelting furnace. Scrap dealers may also introduce different metals into the UBCs bales, when non-can aluminium is used to complete the bales. Typical impurities found in the UBCs are sand, clay, concrete, plastic containers, glass, moisture, residual fluids, and ferrous and non-ferrous metals (Doutre, 2011), which introduce chemical elements such as Si, Fe, Cu and Mn. Those are chemical elements that are known to limit aluminium recyclability (Hatayama *et al.*, 2007).

Nowadays impurities as a limiting factor for recyclability in the beverage can sector is not a major concern. With the current recycling rates and growth of aluminium applications in the past years, especially in the transport sector, no need to improve the beverage can system has been indispensable. One of the strategies to deal with aluminium scrap from different sources, including UBCs, has been to melt the different aluminium alloys to produce secondary castings, largely used in the automotive sector. Those secondary castings can handle a wide tolerance of impurities, and thereby contain high concentrations of alloying elements (downgraded aluminium). According to Nakajima *et al.* (2010) the concentration of alloying elements in Al-Si-Cu-Mg-Ni castings is around 27%.

With the expected saturation of the aluminium market in the automotive sector by 2018 ± 5 (Modaresi & Müller, 2012), the use of secondary castings is not expected to grow in the future. Therefore, there will be an increased interest to keep the UBCs in a close loop, can-to-can system. In such scenario, the impurities will play an important role in the recyclability of cans. To "close the loop" means that the scrap should return to the sector where a product was produced in order to avoid variations in the alloy composition of secondary aluminium. In theory it is technologically feasible to close the loop without compromising the functionality of the products (The Aluminum Association, 2011). In practice, cans recycling faces problems that impede higher recycled content such as, can collection and recovery systems, allocation of the collected cans according to price/market demand to other sectors, as well as the introduction of impurities.

Previous studies on aluminium were predominately performed in specific sectors, such as transport or buildings, or multisectoral aluminium recycling. Comparatively, fewer studies were carried out to improve recycling of aluminium cans. Finding the process and quality limitations of the current aluminium beverage can system will be used to estimate recyclability of scrap in the future.

1.2 Previous studies on UBCs recycling

Many studies on UBCs focused on the processes for aluminium recycling to avoid entry of contamination and improve quality by reducing the mixture of different aluminium alloys. Gaustad *et al.* (2012) indicated that impurities in aluminium, compared to other metals, cannot be easily removed by thermodynamic processes, and therefore strategies should be addressed along the production processes to preclude accumulation of impurities. Physical separation such as magnetic, air separation, eddy current separation among others is explained in detail. Rabah (2003) suggested a method to recover aluminium-magnesium alloys from UBCs by augmenting the removal of the can's coating.

Other studies concentrated on the removal of impurities during the remelting process. Le Brun *et al.* (2007) explored different methods for the purification of aluminium from impurities such as Fe, Mn or Si. Nakajima *et al.* (2010) evaluated the quantitative removal of impurities during the remelting process, by modifying different parameters, in order to assess the impact of those parameters in the amount of impurities removed. Gaustad *et al.* (2012) presented different methods for impurities removal. The extraction of impurities from the molten metal was explained, highlighting the thermodynamical and economical barriers, in addition to the environmental downside.

Buffington (2012) identified the role of the secondary aluminium market in the total recyclability of UBCs, pointing out that the low recycled content is, to a high extent, due to a lack of innovation to make a more efficient and integrated UBCs supply chain. Gaustad *et al.* (2011) studied the importance of recycler's decisions in the accumulation of tramp elements. The study concluded that improving market-driven decisions and upgrading technologies is necessary to avoid accumulation of tramp elements, hence increasing scrap use and reducing greenhouse gas emissions. This study used a dynamic material flow analysis model (dMFA) to quantify the accumulation of impurities in the future; closer the approach of the present study. The authors highlighted that constraining elements are different according to the way the scrap dealers allocate the scrap. With the current market based scrap allocation, Fe and Mn will become constraining elements. However, the aluminum beverage cans system is a more close-loop case than other sectors, and therefore a cleaner and more specific alloy composition is expected. Hatayama *et al.* (2007) conducted a dynamic substance flow analysis of the Japanese aluminium sector. The results indicated that no change in the concentration of alloying elements is expected until the year 2050 for aluminium cans. According to Hatayama, this is because only mill products are expected to be used for the beverage can. However, in the case of close-loop aluminium beverage can system, this scenario will probably change, and the concentration of alloying elements may increase.

1.3 Research gap

A visualization of the interactions between the different processes and flows of the beverage can sector will help us to identify the main barriers to reach a can-to-can system, and also to comprehend the terms and different definitions used by the aluminium sector in the USA. By understanding the whole system, it will be easier to locate the impurities entry points, so that the right decisions to improve the processes are taken. If a high recycling rate and a close loop system are achieved, there will be need to estimate the concentration of impurities in the secondary scrap. Most of the previous studies are not addressing the specific case of aluminium cans, and those estimating impurities in aluminium cans do not explore the accumulation of impurities in the future. Thus, a model showing the accumulation of impurities in the cans stock will be critical to assess the feasibility of a 75% recycling rate and a close-loop system.

1.4 Research goals

This thesis will try to identify the most important quality-related barriers to closed-loop recycling of aluminium beverage cans on a regional scale and explore potential solutions. The research will be conducted by creating a detailed model for beverage can recycling using the material flow analysis framework. This model will track various chemical elements through the cycle, and include all relevant entry paths of contamination to the system, such as coatings and non-UBC scrap. Quantification of the system will mainly be based on literature review, and complemented by sensitivity analysis with respect to key parameters.

The thesis will focus on answering the following questions:

i. Where are located the main losses of aluminium in the beverage can sector, and what are the reasons for those losses?
ii. What and where are the main entries of impurities into the system, and how does the entry of impurities into the aluminium can system may affect negatively to the target of increasing the recycled content of the cans?
iii. What measures can be taken to improve the recycling rate and recycling content in the cans, and what are the limitations for the measures taken?

2. Methodology

To quantify the flows within and across the system boundaries, a material flow analysis (MFA) model is used. Currently MFA results are employed to discuss topics as recycling, energy efficiency and green-house gas emissions, trade, as well as forecasting future scenarios, owing to its simplicity to understand the flows and interactions, and its capacity to trace and calculate the concentration of alloying elements (Bertram *et al.*, 2009). As the alloying elements concentrations in the aluminium is an important limiting factor for increasing recycling rates, the alloying elements and Al are tracked with a substance flow analysis (Boin & Bertram, 2005).

2.1 System definition

2.1.1 System Boundaries

The cans recycling systems are different in different regions. The USA represents one of the largest markets of aluminium cans consumption in the world, while UBCs constitute the largest source of aluminium scrap in the U.S. and, together with durable goods, the major source of aluminium disposed in landfills (Liu *et al.*, 2011). Furthermore, aluminium cans represent the second largest application of aluminium products, only after transportation. Moreover, the USA is the largest producer of secondary aluminium (Buffington, 2012). Figure 2 shows the share of end use products in the USA/Canada for the year 2009 obtained from (GARC, 2009), where aluminium cans represent 20% of the total aluminium consumption. The long tradition of aluminium consumption in the USA together with data availability is the reason to select the USA as system boundaries.

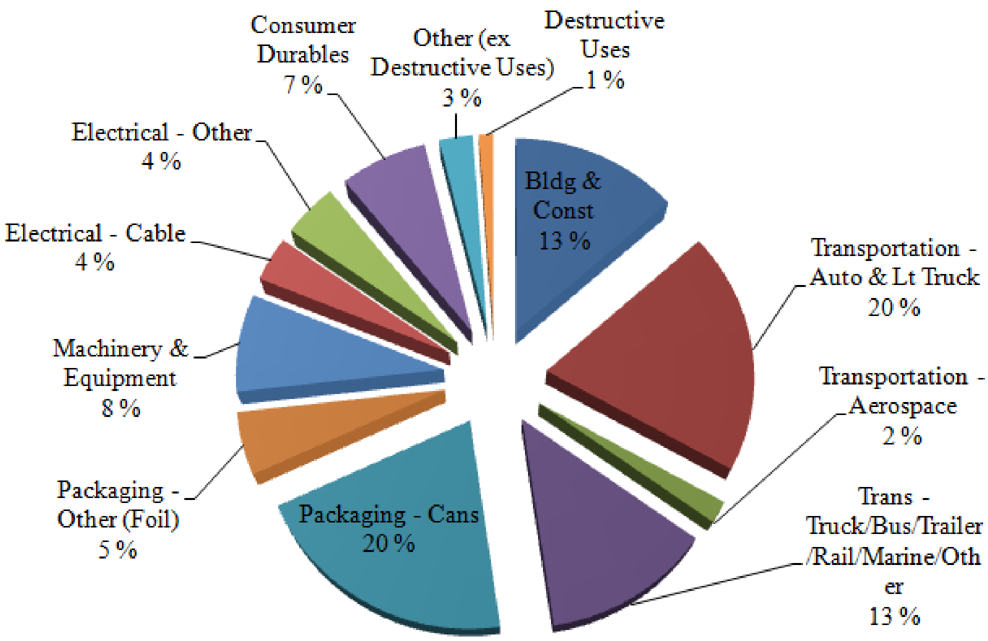

Figure 2: Share of use of aluminium by end-user applications in the USA/Canada in 2009 (GARC, 2009)

The system includes the most important processes in the production of aluminium cans with recycled aluminium, including manufacturing and semi-manufacturing processes for secondary aluminium, use phase and collection systems. Primary aluminium is used only as an inflow of metal into the system. Other processes such as collected aluminium from non-can sectors are not included within the system boundaries.

A static model is used to show interactions of the flows and processes involved in recycle of UBCs in the USA. A dynamic model is used to show accumulation of impurities in the recycling system, which can lead to a saturation of alloying elements, and therefore to a surplus of collected UBCs under certain conditions.

Different aluminium can sizes are found in the beverage market. In this study the standard 0.33 L (12 Ounce) can is used as the case study, because it represents the largest type of aluminium can consumed in the USA. However, for the static model, all the different can sizes were included for the quantification (due to data availability).

2.1.2 Static model system overview: processes and flows in the system definition

8 processes are included in the static model. Those processes are an aggregation of several sub-processes, in order to simplify the calculations and due to data availability. Figure 3 visualizes the simplified system with the stages related to the production of secondary aluminium for the static model.

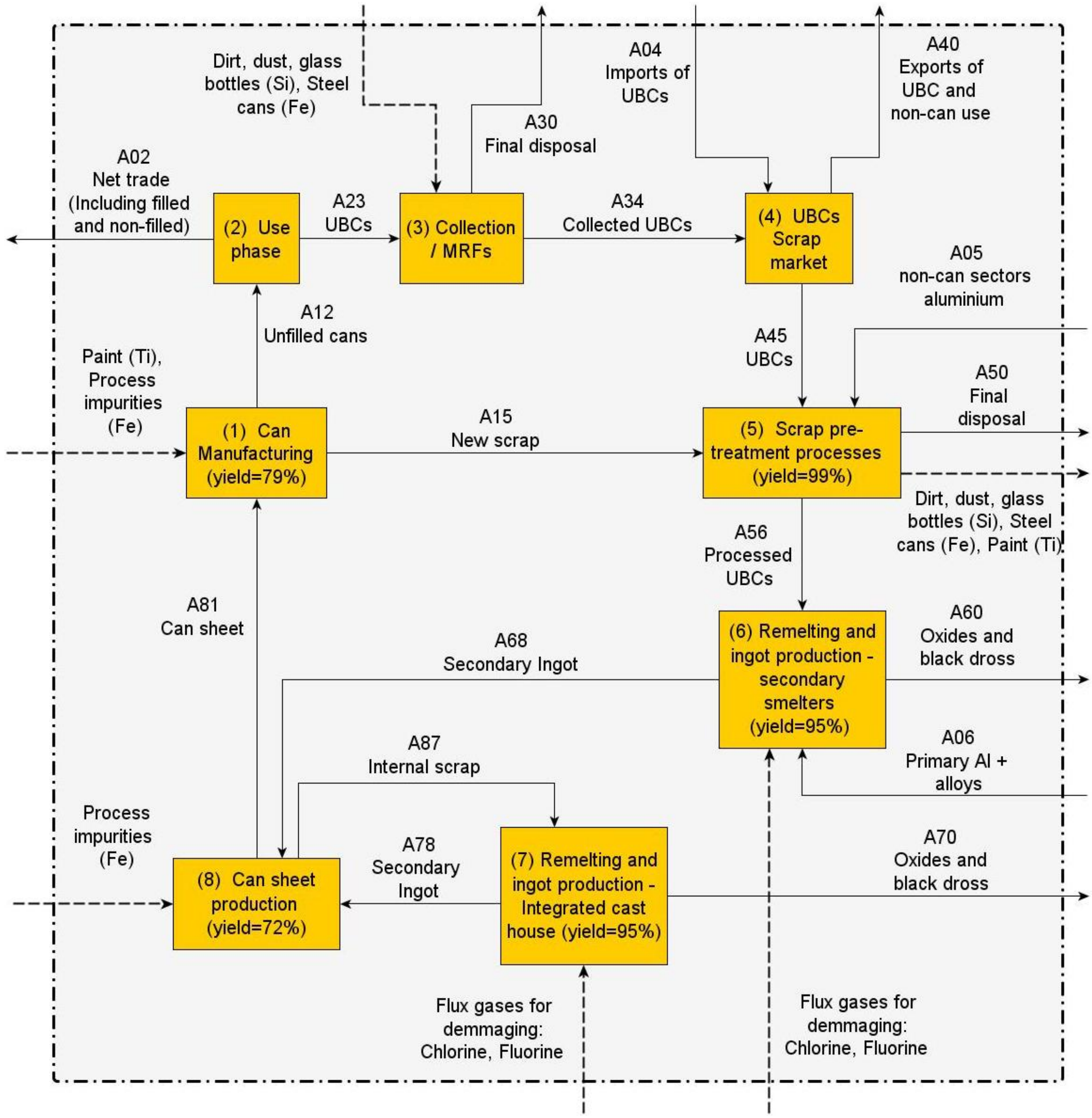

Figure 3: System definition of secondary aluminium for the static model in the USA

The processes are portrayed with rectangles while the aluminium flows (including alloying elements) are represented with arrows. The dashed arrows symbolize flows of other substances, such as impurities or gasses. Those dashed arrows are just for representation of impurities entry points and not quantified in the static model. In the descriptions of the processes presented next, the main causes of aluminium losses in the system are also described.

Different terminologies are used in this thesis. Post-consumer UBCs are the total cans received by the material recovery facilities (MRFs) after the use phase (A_{23}). Collection rate (CR) is the yield of recovered cans in the MFRs. Collected or recovered cans (A_{34}) are those cans to be reused in new products (not necessarily to produce new cans). In this thesis the terms collected cans and recovered cans are used indistinctly. Recycled cans are the UBCs that were collected and used to produce new cans.

Process 1 - Can manufacturing

The most common aluminium beverage can sold in the USA is an assembly of a body, a lid and a tab. The body is where the beverage will be contained and is the heaviest part of the can; around 82 wt % (Detzel & Mönkert, 2009). It has a thick domed base but a very thin curved shape wall (Wootton 1994), varying from close to 0.25 mm in the bottom to 0.10 mm in the upper section of the wall (Doutre, 2011). The lid, also named end, is the cover that is placed on the top of the body to seal the can after the beverage is filled. Because of its flat shape, it has a thicker gauge than the body wall (Hosford & Duncan, 1994). The tab is the component assembled together with the lid that serves to open the can. The lid together with the tab represents the other 18% of the weight of the can. Figure 4 visualizes the parts of the aluminium beverage cans.

Figure 4: Standard 0.33L aluminium beverage can. The body is portrayed on the left. The lid and tab are shown on the right (REXAM, 2013)

Figure 5 shows the processes and flows entailed in the production of cans. It is important to mention that the filling of the can with the beverage takes place in a separate location than that of the manufacture of the can. The final assembly takes place at the beverage filling facilities after the can is filled. Due to lack of information about the tab manufacturing, only basic manufacturing processes for the tab are portrayed. The can manufacturing companies receive aluminium sheets from the mills; flow A_{81}. The scrap generated in the can manufacturing companies (new scrap) is sent to secondary smelters where ingots are produced; flow A_{15}. The bodies and lids are sent to beverage companies where they are filled and then sent to the consumers (use phase). In this system definition, the filling companies are not shown, thus the flow from the can manufacturing goes straight to the use phase; A_{12}. The largest can manufacturing losses occur during the cut-press process for the body and lid. In theory, this scrap represents 9% of the total losses in the can manufacturing process. In practice, it is around 12 to 14% (Wootton, 1994). Additional losses occur during the process of trimming the top ends of the can's bodies, of around 6 mm from the top (Hosford & Duncan, 1994). Rejection rates of cans are around 1 can per million (Doutre, 2011). Considering all the manufacturing losses, the aluminium cans manufacturing has a total yield of approximately 79% (PE Americas, 2010).

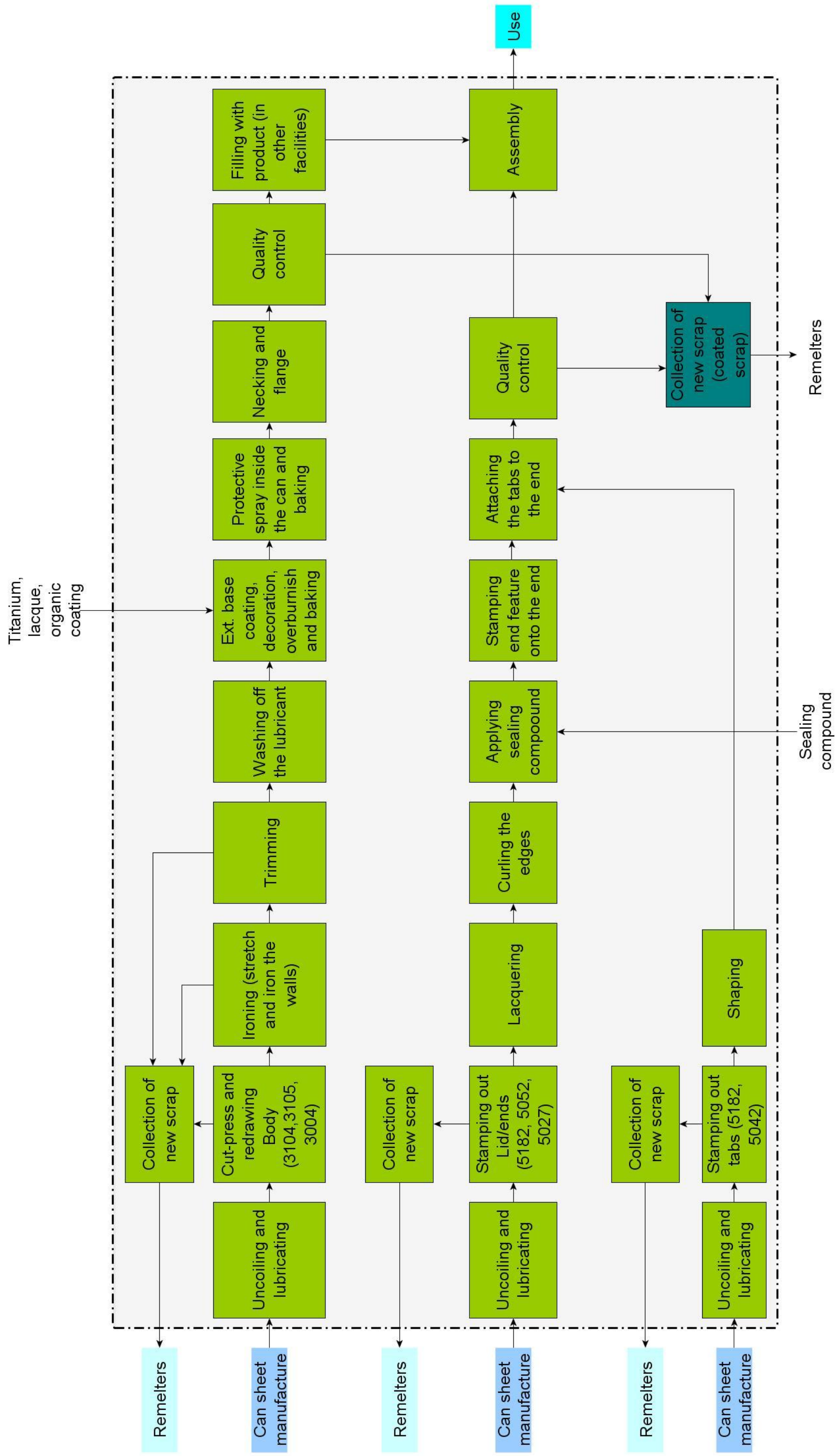

Figure 5: Processes and flows of aluminium can manufacture

Process 2 - Use phase

The use phase is where the consumption of the beverage takes place. The beverage cans are shipped internally from the domestic producers (A_{12}) and also traded. Trade (A_{02}) may occur before or after the filling of the beverage, but in this system definition it is aggregated into one single flow. After the use phase the cans are sent to the UBCs collection systems (A_{23}). 1272 kilotonnes of aluminium were used to produce cans in the USA in 2010 according to the Can Manufacturers Institute (CMI, 2012). CMI states that the cans are recycled and transformed into a new can only after around 60 days. That means that a single can is recycled around four times per year. Compared with other sectors such as construction or automotive, the time-span of aluminium in the use phase is negligible.

Process 3 - UBCs collection system and material recovery facilities

This process includes the collection of aluminium cans inside the USA by the diverse collection systems and gathered at the Material Recovery Facilities (MRFs). The can collection programs in the USA are typically conformed by drop-off sites, curbside, and container deposit legislation (Greenblue Institute, 2011).

- Drop-off program: the users bring their own cans to centralized locations. The drop-off program takes place predominately in rural areas, owing to economical and environmental reasons (mainly to avoid long distances traveled by the collection trucks).
- Curbside program: operates in high density areas for efficiency and cost-effectiveness, where trucks collect the cans (as well as other recyclables such as paper, glass and plastic). Additionally, the curbside program can either be "single stream" or "dual stream". In the single stream, all the recyclables are put together into a single container. In the dual stream an additional container is used to sort paper or glass separately.
- Container deposit program: the user deposit the can in a redemption center, where a deposited credit is returned to the user for each beverage can. This deposited credit was paid by the user at the time the beverage was purchase.

Figure 6 visualizes the use phase, the collection programs, and the UBCs treatment processes at the MRFs.

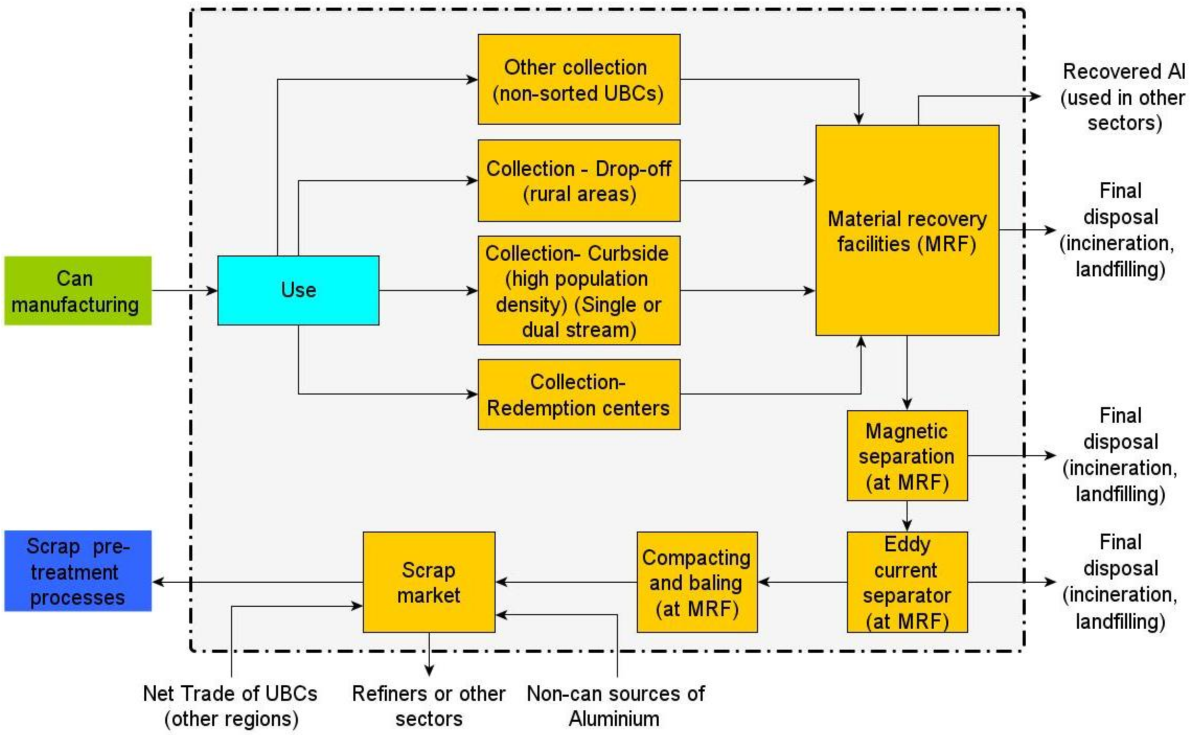

Figure 6: Processes and flows involved in the use phase, collection programs and treatment of UBCs

In the MRFs the non-magnetic UBCs are separated from magnetic materials, such as steel cans, and from non-current conductive material, such as plastic or wood. The sorted aluminium cans are later compacted, baled and transported to the scrap dealers. The scrap dealers act as the link between the MRFs and the aluminium producers with their built-in collection and transportation systems (Plunkert, 2006). The scrap dealers sell the baled UBCs to the remelters, for ingot production, or to refiners, to produce cast alloys.

Discarded cans (A_{30}) are the largest losses of metal in the whole system. According to the United States Environmental Protection Agency (EPA, 2011), from the around 1240 kilotonnes of post-consumer UBCs in the USA in 2010, only around 620 tonnes were collected (A_{34}), while the rest was lost in landfills or incinerated (A_{30}). One of the reasons for these losses is the collection system after the use phase. Due to lack of dedicated collection and recovery systems for aluminium cans, a large amount is discarded. Cans recovered from commingled waste (not sorted at the use phase) is not accepted by the UBCs recycling facilities, as it is contaminated with substances from the general waste. Cans obtained from commingled waste might be remelted to produce low-grade Remelt Scrap Ingot or RSI (Das *et al.*, 2007). Dedicated collection systems, such as the deposit legislation enhance the cans collection in many countries. This situation is reflected in figure 7. The highest collection rates occur in countries with container deposit legislation. According to the European Aluminium Association (EEA, 2011), Estonia is a particular case, where a large share of cans is acquired by residents in Finland, owing to its lower cost.

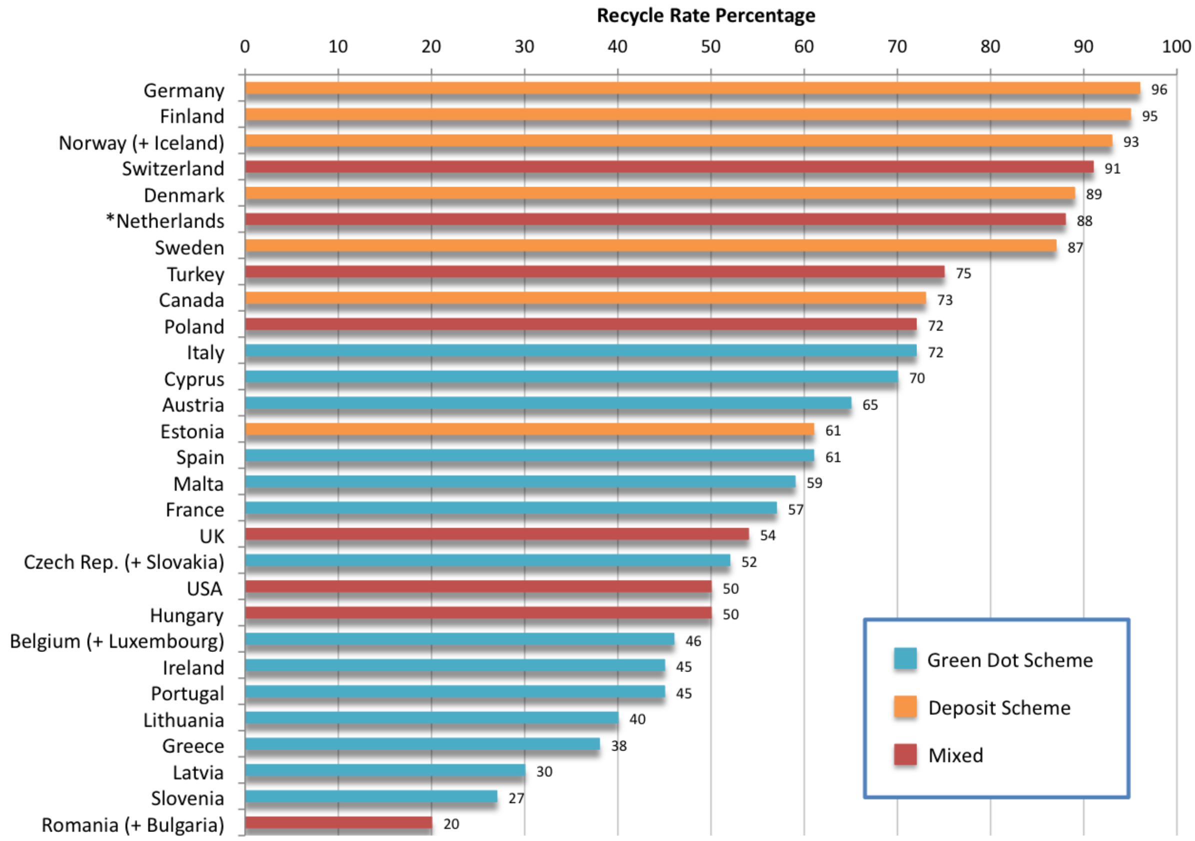

Figure 7: Comparison of collection rates for aluminium beverage cans in Europe, USA, and Canada in 2010 (Can Recycling Institute - CRI, 2012a)

Figure 8 shows the collection rates difference between states with deposit system and without deposit system in the USA. The collection rate is more than double in states with deposit system.

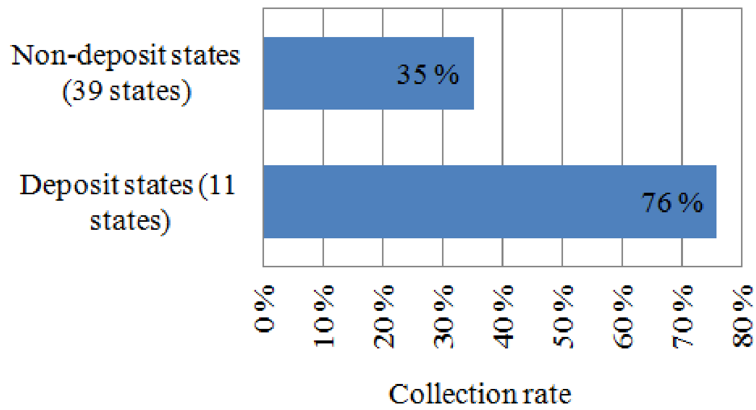

Figure 8: Collection rate in the USA depending on the collection method (CRI, 2006)

Part of the aluminium industry in the USA is against changing the current collection systems as it might represent economic losses to the beverage can companies and the MRFs. Even though UBCs play a small percentage from the total waste processed, it is often essential for the MRFs survival (Plunkert, 2006). In the waste stream UBCs are more valuable material than paper or plastic (Green & Skillingberg, 2006). A deposit system will require sufficient market penetration to be cost-efficient. A mandatory change to a deposit system could have detrimental market consequences as occurred in Germany, where an imposed deposit system led to the collapse of the can market in 2002 (EEA, 2011). Furthermore, collection rates are not easy to increase without additional regulations and economic incentives (The Aluminum Association, 2011).

Low primary aluminium prices and increase in new scrap generation has the potential to mitigate UBCs recycling. Therefore increase in post-consumer collection may not necessary lead to higher utilization of recycled aluminium, as the market is actually driven by the price and utilization of primary aluminium. In other terms, it is not enough to increase the collection of aluminium cans. To increase the recycling rate, it will be necessary to improve the UBCs supply chain by integrating the upstream and downstream processes in order to give higher commercial value to the UBCs (Buffington, 2012).

Process 4 - UBCs scrap market

The collected UBCs are sent to the scrap market (A_{45}). Part of the collected UBCs are exported or used as material for other sectors (e.g. automotive) (A_{40}) and some are used to produce new cans (A_{45}). UBCs exported to other countries might end up in low quality applications. For example UBCs exported to Mexico would most likely become part of cast-alloy aluminium, due to lack of technology to produce can-grade aluminium sheet (The Aluminum Association, undated). Green & Skillingberg (2006) indicate that in the USA over 95% of the collected UBCs is used to produce new aluminium sheet. Imported UBCs (A_{04}) are used to produce new cans in the USA. In 2010, UBCs imported from other countries were 119 kilotonnes (around 19% of the collected within the USA). Exports on the other hand were only 28 kilotonnes (CMI, 2012). The difference between imports and exports makes the USA a net UBCs importer.

Process 5 – Scrap pre-treatment processes

The collected scrap is pre-treated to eliminate lacquers, paints, paper and plastic labels (Gaustad *et al.*, 2012). New scrap from can manufacturing (A_{15}), old scrap from UBCs (A_{45}) and aluminium scrap from non-can sectors (A_{05}) are shredded, filtered, separated from non-aluminium material, and decoated (delacquered). As remelting UBCs without a previous decoating process lead to higher aluminium losses (due to increased metal contamination and oxidation), higher gaseous emissions and higher consumption of salt flux (Kvithyld *et al.*, 2008), delacquering is a standard process in the remelting facilities. Among other benefits, delacquering will increase the metal yield, reduce energy use, lower emissions, reduce salt/flux usage, reduce dross formation and reduce the risk of explosions in the furnace due to water content (Kvithyld *et al.*, 2004). In the delacquering process the paint and lacquers, which conforms less than 2% of the total weight of the can (Zuo & Zhang 2008) are roasted at a temperature below the aluminium melting temperature. The sorted, dried and delacquered aluminium is sent to the remelting furnaces. Figure 9 shows the scrap pre-treatment processes.

With a process yield close to 99% (PE Americas, 2010), most of the pre-processed scrap is available for remelting (A_{56}). A small percentage is lost and irretrievable for the aluminium can industry (A_{50}). The losses of aluminium in the pre-treatment processes include (Greenblue Institute, 2011):

- Losses in the magnetic separator: UBCs are sorted from magnetic material. If the UBCs are assembled with other magnetic component (bi-metal cans), aluminium may be segregated as a magnetic material.
- Losses in the eddy current separator: Inadequate relationship between the cross-section to the surface areas of shredded aluminium in an eddy current separator might not generate adequate electromagnetic field needed for the sorting process and sorted as non-aluminium material.
- Additional aluminium losses might occur in the air separator and screening process.

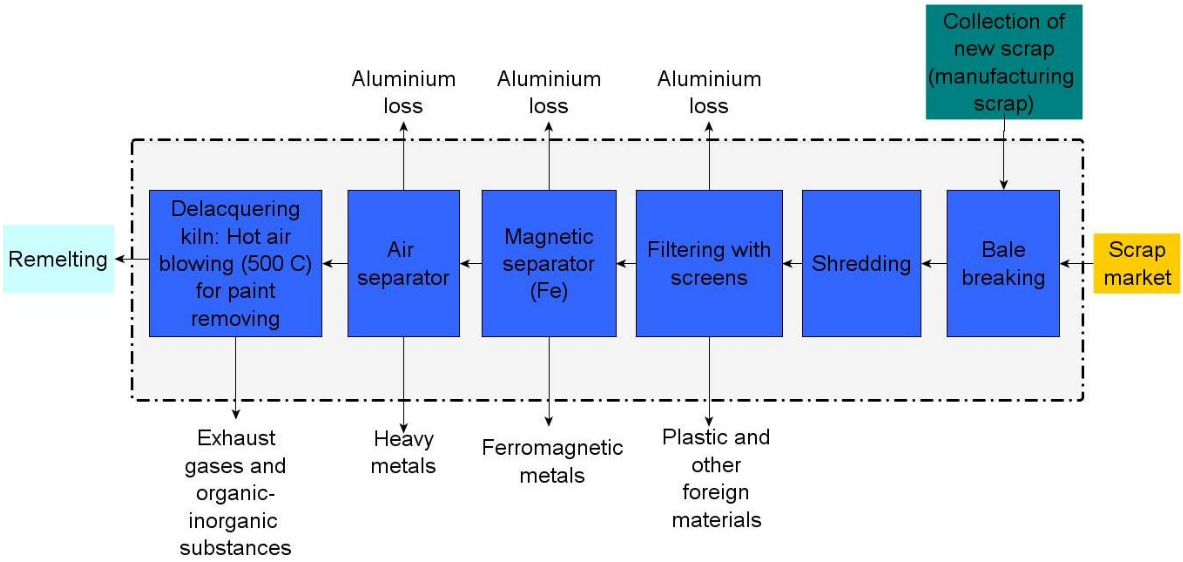

Figure 9: Scrap pre-treatment processes

Process 6 - Remelting and ingot production by secondary smelters

The pre-processed aluminium is melted, the alloy composition adjusted, the molten metal is separated from the skimmings and finally poured into molds to produce ingots. The whole process has around 95% manufacturing yield (PE Americas, 2010). According to the Aluminum Association (2011), most of the aluminium used in the remelting process is scrap (A_{56}). Primary aluminium and alloying elements (A_{06}) are added to adjust the chemical composition. Around 5% of total losses, such as dross and oxides are irrecoverable for the aluminium can sector (A_{60}). The ingot is then sent to the mills to produce can sheets (A_{68}).

Secondary aluminium producers obtain large amount of clean scrap (new scrap) from industry. This new scrap may be obtained directly from the source in a manufacturing facility, and is typically conformed of single aluminium series separated by product type and reprocessed into the same alloy associated with the product (Greenblue Institute, 2011).

Some remelting facilities use aluminium from non-can sectors together with the UBCs. Sources of scrapped aluminium from packaging, such as bottles (1000 or 3000-series) or rigid containers (3000 or 5000-series) might be used in the production of aluminium cans. On the other hand, composite blister packs (pharmaceutical use), peel-away closures (food), and metalized film and paper (decoration) are rapidly oxidized due to its reduced thickness and therefore rarely used for can manufacturing. Aerosol cans are not included in recycling programs due to security reasons, as they might contain flammable hydrocarbon-based propellants and expand rapidly during the baling, or create a fireball if added to the remelting furnace. Small size aluminium products such as screw tops (5000-series) may be screened out and never reach the processing plant. Aluminium trays may be rejected from recycling programs due to health concern related to food and oil residues. Rigid plastics entering the remelting furnaces may create "hot spots" speeding up oxidation and increasing aluminium losses (Greenblue Institute, 2011). Recycled computer cases, bicycle frames, aluminium cooking pots, or windows frames may be used to produce aluminium beverage cans (The Aluminum Association, 2011).

The pre-processed scrap is remelted typically in a reverberatory furnace. Molten salt flux such as NaCl or KCl might be added during the remelting process to trap impurities, which will then float at the top of the molten metal. This layer acts also as a protective barrier, preventing the molten aluminium from oxidizing. As the remelted UBCs contain a concentration of Mg above the established for can body manufacturing, it is necessary to remove some magnesium through a process named "demmaging". Chlorine or fluorine gasses are incorporated into the molten aluminium, forming a solid material with Mg that will rise to the surface (Margolis, 1997). However, this process generates losses of aluminium, because aluminium itself is also chlorinated (Nakajima *et al.*, 2010). The blend of all the floating materials is named skimmings. After cooling down and solidifying, the skimmings are named dross (Greenblue Institute, 2011). In the skimmings, the alloying elements form compounds with Al, and might have a different concentration of alloying elements than the useful metal (Le Brun *et al.*, 2007).

The molten aluminium is poured into a holding furnace where the alloy composition is adjusted to the industry requirement by adding alloying elements and primary aluminium. The molten metal is filtered from the remaining oxides before it is casted into molds to produce the ingots (direct chill casting method) (Yoshida & Baba, 2010). The solidified ingots are scalped to meet dimensional specifications and sent to the can sheet producers.

The remelting and ingot production by the integrated cast houses (Process 7) is basically the same as the ingot production from secondary remelters, but using in-house scrap (internal scrap) from semi-manufacture products (aluminium coil production) as source of aluminium.

Figure 10 visualizes the flows and processes entailed in the body ingot production. The manufacture of the lid and tab is currently not using UBCs, and they are normally manufactured with primary aluminium.

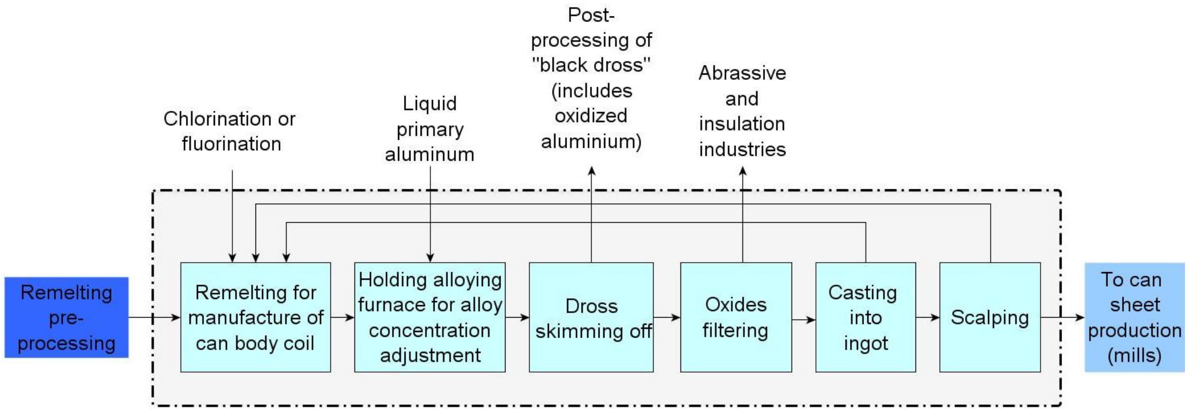

Figure 10: Remelting and ingot production processes by secondary smelters

Process 8 - Can sheet production

The can sheet production facilities are often located next to the remelting facilities (EEA, 2008). This configuration receives the name of integrated cast house. In the can sheet production facilities (or mills), the body, lid and tab coils are produced. This includes pre-heating, hot and cold mills thickness reduction and shearing. In the production of the coils, around 28% scrap is generate, which is named "internal scrap or home scrap". This scrap is sent to the integrated cast house for the production of new ingots (A_{87}), and used later to produce new can sheets (A_{78}).

During the transformation of the ingot into coil, the edges and ends of the coil are removed to fit the dimensions needed for the machines and the final dimension required by the customer. This internal scrap is sent back to the remelters, and not considered in the calculations of the recycled content (PE Americas, 2010). The coils are finally sent to the can manufacturing companies (A_{81}).

Figure 11 shows the processes and flows in the mills. This is a representation of the body can sheet production, but basically illustrating the same processes needed for the lid and tab sheet production. The coil for the lid manufacture may receive a coating before it is delivered to the can manufacturers (PE Americas, 2010).

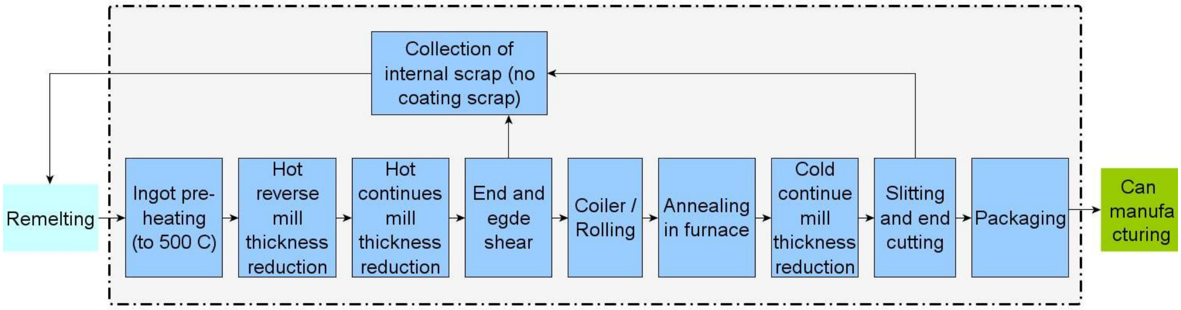

Figure 11: Can sheet production processes

2.2 Recycling rate and recycle content definitions

2.2.1 UBC Post-consumer recycling rate

The recycling rate of old scrap (UBCs) indicates the percentage of the produced aluminium cans that are recovered to produce new aluminium cans. A higher ratio indicates that more scrap is recycled. However, different organizations present their own recycling rate definition. The Aluminum Association and the Can Manufacturers Institute (CMI) publishes information about the recycling rate and recycled content in an unclear way. The Container Recycling Institute (CRI) on the other hand publishes information showing the difference in the recycling rates formulas. The formulas and calculations are based on data from the Aluminum Association, CMI, CRI and EPA (The Aluminum Association, 2003; The Aluminum Association, 2012; EPA, 2011; CMI, 2010; CMI, 2012; CRI, 2013). The Aluminum Association and CMI calculate the recycling rate as follow:

$$Recycling\ rate = \frac{No. of\ UBCs\ collected\ from\ the\ MRFs\ including\ those\ exported\ for\ recycling + No. of\ imported\ UBCs\ from\ other\ countries}{No. of\ total\ cans\ made\ and\ shipped\ in\ the\ USA\ (including\ those\ exported)}$$

$$= \frac{A_{34} + A_{04}}{A_{12}}$$

For the year 2010, the recycling rate according to the Aluminum Association and CMI is:

$$= \frac{46.92\ billions\ cans + 9.02\ billions\ cans}{96.29\ billions\ cans} = 58.1\%$$

On the other hand, The CRI and EPA define the recycling rate as (CRI, 2013) follow:

$$Recycling\ rate = \frac{UBCs\ collected\ from\ the\ MRFs\ including\ those\ exported\ for\ recycling}{Total\ cans\ made\ and\ shipped\ in\ the\ USA\ (including\ those\ exported) + New\ imported\ unfilled\ cans - New\ exported\ unfilled\ cans}$$

$$= \frac{A_{34}}{A_{12} + A_{01} - A_{10}}$$

Even though CRI and EPA agree in the method to calculate the recycling rate, CRI shows their calculation using the number of cans, while EPA uses a weight unit (Short-tons in EPA publications). The problem of calculating the recycling rate with the number of cans is the variety of can sizes (i.e. 12 ounces or less, over 12 ounces & less than 1 gallon, over 1 gallon). Apparently CRI calculates the total filled and unfilled cans by summing the number of cans, despite the size differences. For the year 2010, the recycling rate according to CRI will be:

$$= \frac{46.92\ billions\ cans}{96.3\ billions\ cans + 1.37\ billions\ cans - 3.67\ billions\ cans} = 49.9\%$$

EPA calculates the recycling rate by using the weight of the cans instead of the number of cans. This results in a recycling rate of 49.6%, which is slightly different than the value obtained by CRI. It is likely that EPA includes trade of filled cans in the calculations, because they calculate the recycling rate using the total post-consumer UBCs and the collected UBCs at the Material Recovery Facilities. The apparent trade (imports – exports) of filled cans is assumed to be negligible with regard to the total number of cans produced.

However, the most important difference is between CRI/EPA and CMI/Aluminum Association recycling rate definitions. The recycling rates calculated with both definitions are presented in figure 12. This figure shows that the recycling rates calculated with CMI/Aluminium Association definition is always higher than the calculated with CRI/EPA definition.

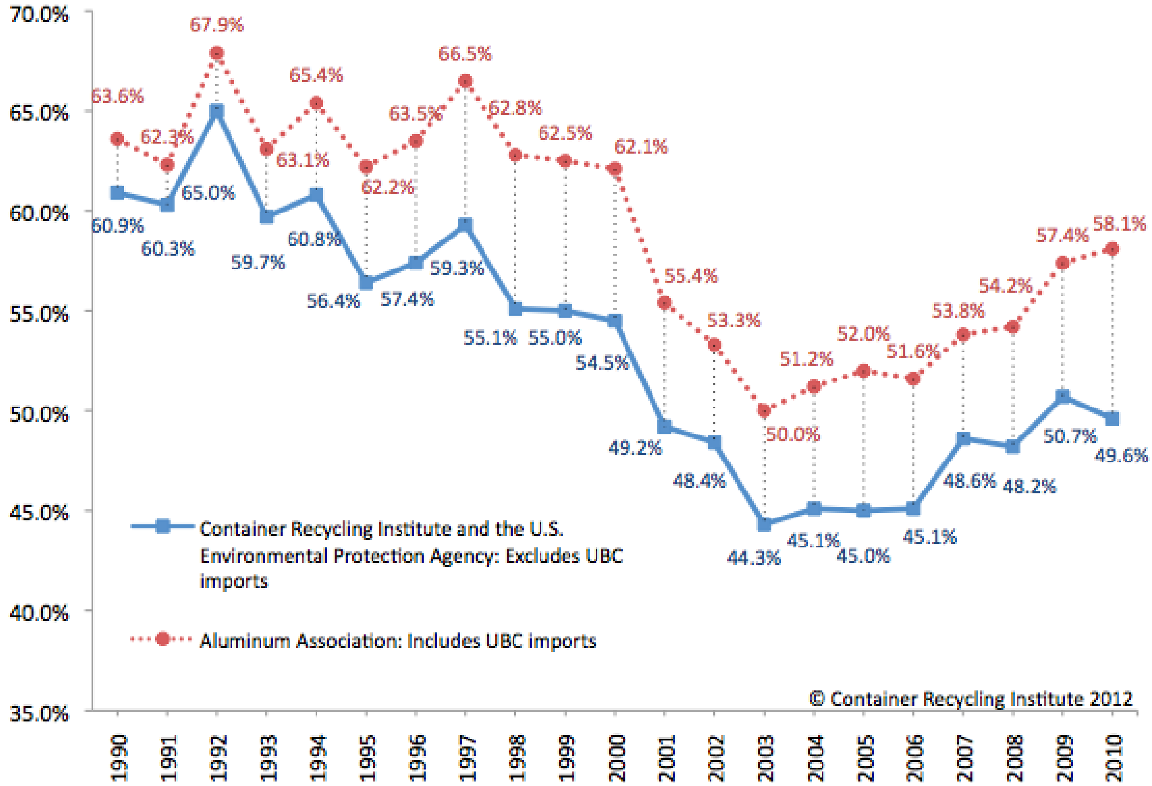

Figure 12: Aluminium can recycling rates in the USA (1990-2010) (CRI, 2012b)

According to CRI (2013), the difference in the recycling rates results was not so significant before 1990, because imported aluminium cans represented only a small share of the total collection. After 1990, UBCs have been imported from countries such as Mexico and Canada, due to the high demand of recycled aluminium in the USA (CMI, 2012). By including UBCs imports in the calculation, the recycling rate is artificially oversized. The share of imported UBCs grew from 2.2% to 9.4% in 2010 and over 12% in 2011, increasing the difference between the two results. Showing an oversized recycling rate would detract the need to improve the UBCs recycling system in the USA (CMI, 2012).

2.2.2 Recycled content

Rombach (2013) defined the recycled content as the "percentage of recycled metal in the material used for product manufacture". Unlike the recycling rate, the recycled content shows how much aluminium scrap is used to manufacture new products. Because UBCs might be sold to non-can sectors or exported, or on the contrary, non-can aluminium scrap might be used to manufacture cans, then the recycling rate and the recycled content may differ. CMI and the Aluminum Association use two definitions: a post-consumer definition, and a total recycled content definition. The post-consumer recycled content (CMI, 2013) is defined as follow:

$$Recycled\ content\ (post - consumer)$$
$$= \frac{\begin{array}{c} Weight\ of\ all\ the\ UBCs\ collected\ from\ the\ MRFs\ including\ those\ for\ exports \\ -(weight\ of\ exported\ UBCs + weight\ of\ non\ can\ use\ of\ UBCs) \end{array}}{Total\ cans\ made\ and\ shipped\ in\ the\ USA\ (including\ those\ exported)}$$

$$= \frac{A_{34} - A_{40}}{A_{12}}$$

For the year 2010 the recycled content of old scrap would be:

$$= \frac{620 - 37}{1272} = 45.8\%$$

The second definition of recycled content includes pre-consumer scrap (new scrap). For the can manufacturing sector, the recycled content include pre-consumer scrap from can manufacturing facilities, collected UBCs used for can manufacturing, and non-can sectors scrap used for can manufacturing. New scrap generated in the mills and in the remelters facilities are not considered in the recycled content (PE Americas, 2010). The equation is as follow:

Being,

$$\begin{gathered} Z = (Weight\ of\ all\ the\ UBCs\ collected\ from\ the\ MRFs\ including\ those\ exported \\ -weight\ of\ exported\ UBCs - weight\ of\ non\ can\ use\ of\ UBCs \\ +weight\ of\ UBCs\ imports \\ +\ weight\ of\ scrap\ from\ the\ can\ manufacturing\ facilities \\ +\ weight\ of\ non\ can\ scrap\ used\ to\ manufacture\ cans) \\ *\ Scrap\ pre\ treament\ yield \end{gathered}$$

And,

$$k_3:\ Scrap\ pre - treatment\ yield$$

$$Total\ recycled\ content = \frac{Z * k_3}{Z + A_{06}}$$

$$= \frac{(A_{34} - A_{40} + A_{04} + A_{15} + A_{05}) * k_3}{(A_{34} - A_{40} + A_{04} + A_{15} + A_{05}) * k_3 + A_{06}}$$

For the year 2010 the total recycled content is:

$$= \frac{(620 - 37 + 119 + 329 + 151) * 0.9871}{(620 - 37 + 119 + 329 + 151) * 0.9871 + 549} = 68\%$$

2.3 Mathematical model

Two models are developed to understand the impact of different parameters on the system. The static model is used to observe the change of primary aluminium demand when UBCs recycling rate is increased. The dynamic model shows the qualitative limitations of recycling UBCs, due to the limitation of alloying elements concentrations in the recycled aluminium.

2.3.1 Static model of recycling of aluminium cans in the USA

Figure 3 represents the processes and flows of the system definition for the static model. The material flows are represented with the arrows and the processes are represented with rectangles. Some flows enter the system, while others leave the system. For each process the mass balance equation must be satisfied:

$$\Delta S = \sum Inflows - \sum Outflows$$

Where, ΔS is the stock change in the process. Because aluminium cans have a very short time-span (around 60 days) compared to other aluminium sectors, then it can be assumed no stock (S=0) and no stock change (ΔS=0). Then:

$$\sum Inflows = \sum Outflows$$

The sum of inflows into a process should be equal to the sum of outflows from the same process. This equation is also valid for the whole system; the total mass entering the system must be equal to the total mass leaving the system, in absence of stock change.

The collection rate is defined by the efficiency of the MRFs to recover UBCs from the waste stream. The imports, exports and production of cans are dependent of use phase demand. Those flows vary year after year, and therefore, for the static model, those parameters are manually introduced in the model. 8 mass balance equations can be derived from the 8 processes defined:

$$A_{15} + A_{12} = A_{81}$$

$$A_{12} + A_{02} = A_{23}$$

$$A_{30} + A_{34} = A_{23}$$

$$A_{34} + A_{04} = A_{40} + A_{45}$$

$$A_{15} + A_{45} + A_{05} = A_{50} + A_{56}$$

$$A_{56} + A_{06} = A_{68} + A_{60}$$

$$A_{81} + A_{87} = A_{68} + A_{78}$$

$$A_{78} + A_{70} = A_{87}$$

In order to solve the system, additional model approach equations are needed:

$$A_{34} = CR * A_{23}$$

$$A_{12} = K_1 * A_{81}$$

$$A_{56} = K_3 * (A_{15} + A_{45} + A_{05})$$

$$A_{56} = K_4 * (A_{56} + A_{06})$$

$$A_{68} = K_5 * (A_{56} + A_{06})$$

$$A_{81} = K_2 * (A_{68} + A_{78})$$

$$A_{78} = K_5 * A_{87}$$

From the previous equations the flow of primary aluminium can be calculated.

$$A_{06} = \frac{C_2}{K_1 * K_5} * \left(1 + \frac{1-K_2}{K_2} - \frac{K_5 * (1-K_5)}{K_2}\right) - K_3 * \left(C_2 * \left(\frac{1-K_1}{K_1}\right) + CR * C_1 + C_3 - C_4 + C_5\right) \quad \textbf{Eq. 1}$$

Given a recycled content (CR) and the flows C1, C2, C3, C4 and C5 (refer to table 1) primary aluminium inflow can be calculated. For this equation, it is assumed that non-can scrap is remelted together with UBCs, and that primary aluminium is used to dilute the concentration of alloying elements in the molten metal. The recycled content must be manually entered in this equation. In practice, the recycled content is more likely to be a result of the production process rather than an established number. However, to observe the consumption of primary aluminium when the recycling rate and other parameters are modified, the derived equation will show results that can be analyzed.

Table 1: Parameters used in the static model

Process	Parameter
Can manufacturing yield	k1
Can sheet manufacturing yield	k2
Scrap pre-treatment processes yield	k3
Recycled content ratio	k4
Remelting manufacturing yield	k5
UBCs collection rate	CR
Collection of cans (A23)	C1
Production of cans (A12)	C2
Imports of UBCs (A04)	C3
Exports or use of UBCs in other sectors (A40)	C4

2.3.2 Dynamic model for calculating the alloying elements concentration

2.3.2.1 Quantification of the alloying elements concentration in the body

To reach a high recycling rate, it is necessary to understand the limitations of close-loop recycling. The dynamic model is used to monitor the concentration of alloying elements in the body after each recycling loop. The system definition from figure 3 is further simplified to show only the processes that have influence in the concentration of alloying elements in the recycled cans. Those processes are: the lid and body manufacturing, the use phase and the remelting process. Those processes are affected by the collection rate, the concentration of alloying elements in the body and lid, and the impurities entering the system.

Manufacturing losses are not considered in this model, but if the losses are included, the results will basically shift the position of the curves, but not the trends. Trade and non-can use of UBCs are not included in the model. Figure 13 shows the simplified system for the dynamic model.

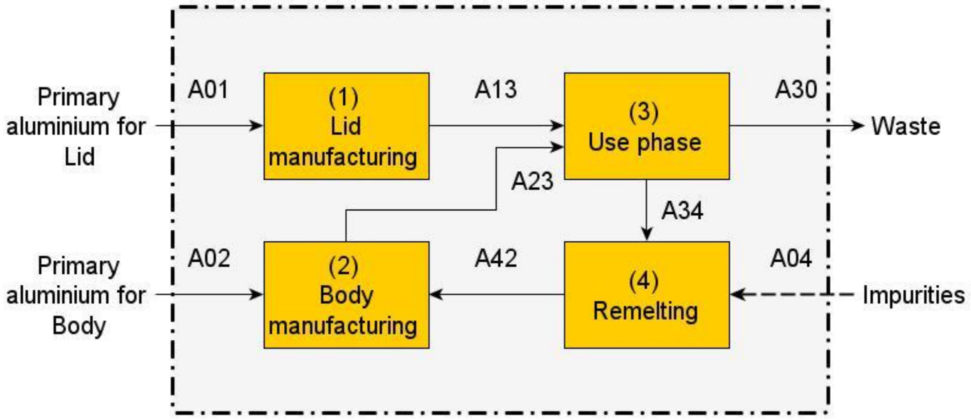

Figure 13: Simplified system for the dynamic model

Currently the UBCs bodies and lids are remelted together to manufacture the body can stock (Process 2). The lid is assumed to be produced from 100% primary aluminium (Process 1). A_{30} and A_{34} are the flows of UBCs after the use phase, where A_{30} is the flow of UBCs lost in landfills or incinerators, and A_{34} is the flow of UBCs collected and used to produce new cans. The mass flow of collected UBCs is defined by the collection ratio (CR). The higher the collection ratio, higher the amount of collected UBCs used to produce new cans. In the dynamic model, the recycling rate is equal to the collection rate, because trade and non-can use are excluded from the system.

In practice, unwanted alloying elements or impurities enter the system principally in the use phase (Process 3). However, impurities inflow in our system is added in the remelting phase to simplify the calculations (Process 4). It is important to notice that this assumption does not affect the results, as the flow in study is the can body flow, A_{23}. To manufacture the body, primary aluminium, A_{02}, is remelted with the UBCs, A_{42}. This primary aluminium contains also alloying elements. The UBCs are the main metal source and the demand is completed with primary aluminium. Therefore a different concentration in the body (A_{23}) is obtained after every recycling loop.

According to the aluminium industry it is possible to produce new cans from 100% recycled material. However, because the lid and the body are melted together, thus changing the alloying elements concentration in the new body, primary aluminium is normally added for dilution. If impurities are entering and increasing the concentrations, even fewer UBCs would be reclaimable.

To calculate the alloying elements concentration in the new body (body + lid) after every recycling loop, mass balance equations and model approach equations are used. Because the body has the largest weight share of the total weight of the can (around 82 wt %), the final alloy composition will be closer to the initial alloy composition of the body. From the 4 processes included in the system, 4 mass balance equations are obtained (S=0):

$$A_{01} = A_{13}$$

$$A_{13} + A_{23} = A_{34} + A_{30}$$

$$A_{34} + A_{04} = A_{42}$$

$$A_{02} + A_{42} = A_{23}$$

The model approach equations shown next describe the relationship between the different flows in a process:

$$\frac{A_{13}}{A_{13} + A_{23}} = \alpha$$

$$A_{04} = A_{34} * \gamma$$

$$A_{13} + A_{23} = D$$

$$A_{34} = CR * (A_{13} + A_{23})$$

Where

α: $Lid\ to\ total\ weight\ of\ the\ can\ ratio$
γ: $Impurities\ entering\ the\ system\ as\ a\ percentage\ of\ the\ total\ flow\ of\ collected\ UBCs$
D: $total\ demand\ of\ metal\ required\ to\ produce\ cans\ (weight\ units)$
CR: $Collection\ rate$

Concentrations:

$C_{01} = C_{13} = C_{lid} = Concentration\ of\ alloying\ element\ in\ primary\ aluminium\ for\ lid$
$C_{02} = C_{prim\_body} = Concentration\ of\ alloying\ element\ in\ primary\ aluminium\ for\ body$

Solving equations:

$$C_{34} = C_{30} = \left(\frac{A_{13}}{A_{13} + A_{23}}\right) * C_{13} + \left(\frac{A_{23}}{A_{13} + A_{23}}\right) * C_{23}^{n-1}$$

$$C_{34} = C_{30} = \alpha * C_{lid} + (1 - \alpha) * C_{23}^{n-1} \qquad \textbf{Eq. 2}$$

Where,

$$n - 1, represents\ the\ concentration\ in\ the\ previous\ loop$$

Additionally,

$$C_{42} = \left(\frac{A_{34}}{A_{04} + A_{34}}\right) * C_{34} + \left(\frac{A_{04}}{A_{04} + A_{34}}\right) * C_{04}$$

Where for simplification,

$$A_{04} \cong 0 \text{ (In the denominator)}$$

Then,

$$C_{42} = \alpha * C_{lid} + (1-\alpha) * C_{23}^{n-1} + \gamma$$

And,

$$C_{23}^{n} = \frac{A_{42}}{A_{23}} * C_{42}^{n} + \frac{A_{23} - A_{42}}{A_{23}} * C_{02}^{n}$$

$$C_{23}^{n} = \frac{CR * D}{(1-\alpha) * D} * C_{42}^{n} + \frac{(1-\alpha) * D - CR * D}{(1-\alpha) * D} * C_{02}^{n}$$

$$C_{23}^{n} = \left(1 - \frac{CR}{1-\alpha}\right) * C_{prim\_body} + \frac{CR}{1-\alpha} * (\alpha * C_{lid} + \gamma) + CR * C_{23}^{n-1}$$

In general for the loop n,

$$C_{23}^{n} = \theta * \sum_{i=0}^{n} CR^{i-1} + CR^{n} * C_{prim\_body}, \forall\, i \geq 1 \qquad \textbf{Eq. 3}$$

Where,

$$\theta = \left(1 - \frac{CR}{1-\alpha}\right) * C_{prim\_body} + \frac{CR}{1-\alpha} * (\alpha * C_{lid} + \gamma)$$

With these equations the concentration of an alloying element after each recycling loop can be calculated.

2.3.2.2 Concentration limit of the alloying elements (plateau)

In a close-loop scenario, the concentration of the alloying elements in the body increases after each recycling loop. This is described by equation 3. However, at a certain point the concentration stops growing and stabilizes in a steady state concentration or plateau. This occurs when the mass flow of the alloying element entering the system is equal to the mass flow of the same alloying element coming out the system. The steady state concentration is used to visualize if one alloy has (or not) reached its upper concentration limit, when the system is already stable (reached its plateau level), under a defined collection rate (CR) and defined rate of impurities entering the system. The next lines show the equations used to calculate the steady state concentration limit.

2.3.2.2.1 Calculation of total aluminium mass flow (including alloying elements)

These equations show how the total mass of aluminium flows was defined. The flows of aluminium (including alloying elements) are replaced by the parameters. The flows with the replaced parameters are visualized in figure 14.

a. Mass balance in the use phase

$$A_{13} + A_{23} = A_{30} + A_{34}$$

$$D * \alpha \; + \mathrm{D} * (1 - \alpha) \; = \; \mathrm{D} * (1 - \mathrm{CR}) \; + \; \mathrm{D} * \mathrm{CR}$$

b. Mass balance in body manufacturing process

$$A_{02} + A_{42} = A_{23}$$

$$\mathrm{D} * (1 - \alpha - \mathrm{CR}) + \mathrm{D} * \mathrm{CR} = \mathrm{D} * (1 - \alpha)$$

Then

$$D * \alpha \; + \mathrm{D} * (1 - \alpha - \mathrm{CR}) + \mathrm{D} * \mathrm{CR} \; = \; \mathrm{D} * (1 - \mathrm{CR}) \; + \; \mathrm{D} * \mathrm{CR}$$

$$D * \alpha \; + \mathrm{D} * (1 - \alpha - \mathrm{CR}) + \mathrm{D} * \mathrm{CR} \; = \; \mathrm{D}$$

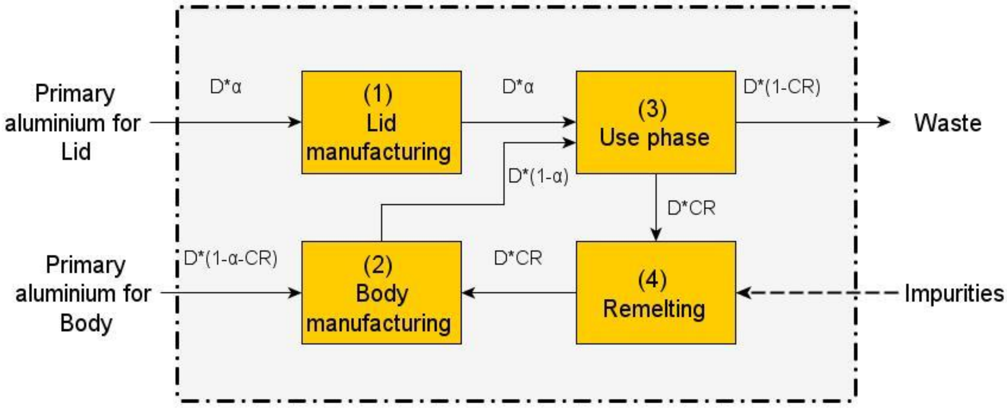

Figure 14: Flow of total aluminium defined by parameters

2.3.2.2.2 Calculation of mass flow of an alloying element

Each of the aluminium flows from figure 14 is then multiplied by the concentration (C) of an alloying element. The representation of the flows of the alloying element is shown in figure 15.

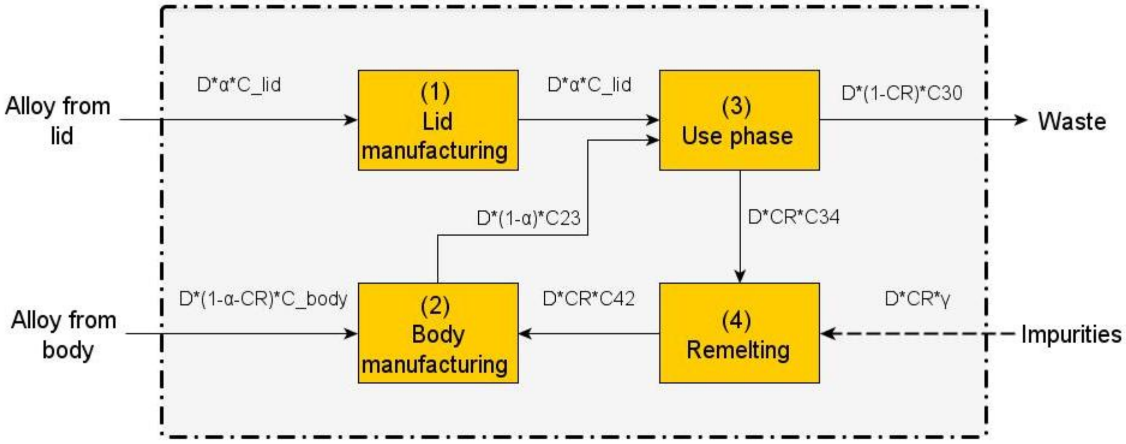

Figure 15: Flows of an alloying element

a. Alloying element mass balance in the use phase (by multiplying the each flow by the alloying element concentration)

$$D * \alpha * C_{lid} + \mathrm{D} * (1 - \alpha) * \mathrm{C}_{23} = \mathrm{D} * (1 - \mathrm{CR}) * \mathrm{C}_{30} + \mathrm{D} * \mathrm{CR} * \mathrm{C}_{34}$$

Where,

$$C_{34} = C_{30}$$

Then,

$$D * \alpha * C_{lid} + \mathrm{D} * (1 - \alpha) * \mathrm{C}_{23} = \mathrm{D} * \mathrm{C}_{30}$$

$$\alpha * C_{lid} + (1 - \alpha) * \mathrm{C}_{23} = \mathrm{C}_{30}$$

$$\alpha * C_{lid} + (1 - \alpha - \mathrm{CR}) * \mathrm{C}_{body} + \mathrm{CR} * (\mathrm{C}_{42}) = \mathrm{C}_{30} \qquad \textbf{Eq. 4}$$

And,

$$\mathrm{C}_{42} = \frac{C_{34} * A_{34} + A_{04}}{A_{34} + A_{04}} = \frac{C_{34} * CR * D + CR * D * \gamma}{CR * D + CR * D * \gamma} = \frac{C_{34} + \gamma}{1 + \gamma}$$

Because 1 >> γ,

$$1 + \gamma \cong 1$$

Then,

$$\mathrm{C}_{42} = C_{34} + \gamma = C_{30} + \gamma \qquad \textbf{Eq. 5}$$

Replacing in equation 4,

$$\alpha * C_{lid} \ + \ (1-\mathrm{\alpha}-\mathrm{CR}) * \mathrm{C_{body}} + \mathrm{CR} * (\mathrm{C_{30}} + \mathrm{\gamma}) = \mathrm{C_{30}}$$

$$\mathrm{C_{30}} = \frac{\alpha * C_{lid} \ + \ (1-\mathrm{\alpha}-\mathrm{CR}) * \mathrm{C_{body}} + \gamma * \mathrm{CR}}{1-CR}$$

Replacing in equation 5,

$$\mathrm{C_{42}} = \frac{\alpha * C_{lid} \ + \ (1-\mathrm{\alpha}-\mathrm{CR}) * \mathrm{C_{body}} + \gamma}{1-CR} \qquad \textbf{Eq. 6}$$

b. Alloying element mass balance in the body manufacturing process

$$D * CR * C_{42} + \ D * (1-\alpha-CR) * C_{body} = D * (1-\alpha) * C_{23}$$

$$CR * C_{42} + \ (1-\alpha-CR) * C_{body} = (1-\alpha) * C_{23}$$

$$CR * \left[\frac{\alpha * C_{lid} \ + \ (1-\mathrm{\alpha}-\mathrm{CR}) * \mathrm{C_{body}} + \gamma}{1-CR}\right] + \ (1-\alpha-CR) * C_{body} = (1-\alpha) * C_{23}$$

$$C_{23}^{plateau} = \frac{CR * \alpha * C_{lid} + \ \gamma * CR + (1-\alpha-CR) * C_{body}}{(1-CR) * (1-\alpha)} \qquad \textbf{Eq. 7}$$

With equation 7 the steady state level (plateau) for each of the alloying elements can be calculated.

2.3.3 Future projections

It is interesting to observe the behavior of the system at high recycling rates. The main reason to pursue high recycling rates is to reduce consumption of primary aluminium, so that less energy is used and less emissions and waste are released to the atmosphere and the ground. By changing parameters, the system behavior can be observed and the processes that need to be improved in the whole recycling system can be identified. For the future projections in the static model, the system was assumed without trade. The results from the dynamic model will show itself the maximum recyclability of UBCs for different collection rates.

2.3.4 Sensitivity analysis

The sensitivity analysis shows how different impurities inflow affects the recycling rate, and how different concentrations of Ti in the lid affect the maximum recycling rate achievable. Basically the results and graphs presented for the dynamic model shows how different parameters (recycling rate, concentration of alloying elements in the lid, and inflow of impurities into the system) are inter-dependent, and how a variation in the concentration of alloying elements in the lid and inflow of impurities into the system affect the maximum recycling rate achievable.

2.4 Data and sources

Data for the mass flows of aluminium cans, UBCs, collection, and recycling rates for the quantification of the static model for the USA market was obtained from the Aluminum Association (2012), Can Manufacturers Institute (CMI, 2012) and the Environmental Protection Agency (EPA, 2011). Data of production yields was obtained from PE Americas (2010). The data gathered to quantify the static flow for the year 2010 is summarized in table 2.

Table 2: Data gathered for the quantification of the flows for the static model

Description	Parameter or flow	Value	Units	Source
Production of aluminium cans	$A_{12} = C2$	1272	kilotonnes	AA & CMI, 2012
Collected UBCs to scrap market	A_{34}	620	kilotonnes	AA & CMI, 2012
Imports of UBCs to the USA	$A_{04} = C3$	119	kilotonnes	CMI, 2012
Exports of UBCs from the USA (not incl. non-can use)	$A_{40} = C4$	28	kilotonnes	CMI, 2012
UBCs received by the MRFs	$A_{23} = C1$	1243	kilotonnes	EPA, 2011
UBCs discarded from the MRFs	A_{20}	626	kilotonnes	EPA, 2011
Can manufacturing yield	k1	79 %		PE Americas, 2010
Can sheet production yield	k2	72 %		PE Americas, 2010
Scrap pre-treatment processes yield	k3	99 %		PE Americas, 2010
Recycled content ratio	k4	68 %		PE Americas, 2010
Remelting production yield	k5	95 %		PE Americas, 2010

The table with the concentrations of alloying elements is presented in section 3.2.1.

3. Results

3.1 The static model - Mass flow of aluminium cans in the USA in 2010

Figure 16 shows the quantification of the flows in the USA in 2010.

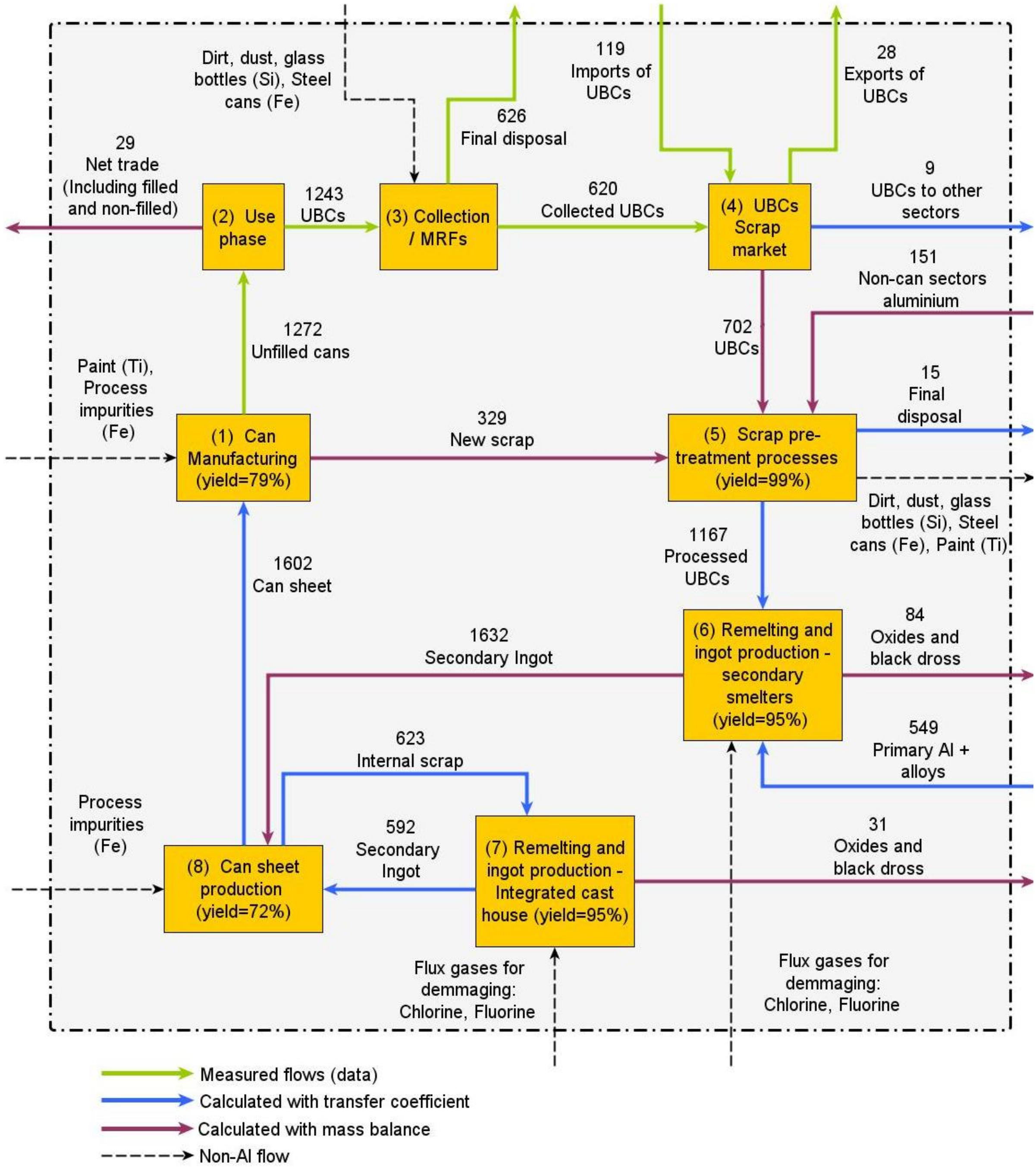

Figure 16: Quantification of the flows of aluminium in the USA in 2010, (in kilotonnes)

One of the difficulties to quantify the system was the lack of reliable trade data for new non-filled cans and filled cans (A_{20}). CRI (2013) presents trade data by can size range, which can introduce errors in the calculation. To avoid this uncertainty, in this thesis the flow A_{20} was calculated by subtracting the weight of produced cans (A_{12}) minus the weight of post-consumer-UBCs (A_{23}). This mass flow (A_{20}) is relatively small compared to the mass flow of the shipped cans, representing around 2 wt %, and should not significantly affect the quantification of the system.

UBCs sold to non-can sectors in the USA were also uncertain because of the difficulties to obtain data of UBCs allocated by sector. In an attempt to quantify this flow, information from Green & Skillingberg (2006) was used. They indicated that "over 95% of the recycled UBCs go back into can sheet". Considering that this report was made for the Aluminum Association, the definition of recycling rate from the Aluminum Association was used to calculate the material sold to the non-can sector. This is:

$$A_{40} = (A_{34} + A_{04}) * 0.05$$

$$A_{40} = (620 + 119) * 0.05 = 37\ kilotonnes$$

It can be considered either that all the 37 kilotonnes were sold for non-can use, or that 28 of those 37 kilotonnes were exported, remaining 9 kilotonnes for non-can use. This is uncertain, but none of the assumptions affect the results in this model (flow of primary aluminium), because in the model, the inflow of primary aluminium is defined by the total recycled scrap used. The total recycled scrap includes UBCs and non-UBC scrap, where the shortage of UBCs is offset with additional non-UBCs aluminium scrap. For the quantification of the system it was considered that the exports were included in the 37 kilotonnes.

Including trade and losses, the total outflow of aluminum from the system in 2010 was around 822 kilotonnes. By far the largest loss of aluminium was the unrecovered UBCs, where around 626 kilotonnes were lost to waste-to-energy facilities or landfills. This represented around 50% of post-consumer UBCs and 76% of the total aluminium leaving the system. The second largest metal loss took place in the remelting process. Around 115 kilotonnes were lost, representing 14% of the total metal loss across in the whole system. Figure 17a shows the share of losses across the system boundaries.

Considering only trade of UBCs and new unfilled and filled cans, the USA imported 53 kilotonnes more than its exports in 2010, forcing the system to use more non-UBC scrap and primary aluminium. Primary aluminium was the main inflow of aluminium into the system with 549 kilotonnes, representing 67% of the total inflow to the system (figure 17b). Likewise, non-can scrap was used to produce new aluminium cans. The use of this non-can aluminium is limited by the uncertainty in the concentration of alloying elements. For example, aluminium from cast alloys contains high concentration of Si that will constrain its use for UBCs. Therefore, aluminium from non-can sectors cannot represent a large share from the total scrap use. Unknown sources of aluminium might challenge the remelters to control the alloy composition. After a quick review of the amount of metal losses and inflow of primary aluminium, it is inferable that consumption of primary Al would be largely mitigated if fewer UBCs were landfilled and incinerated.

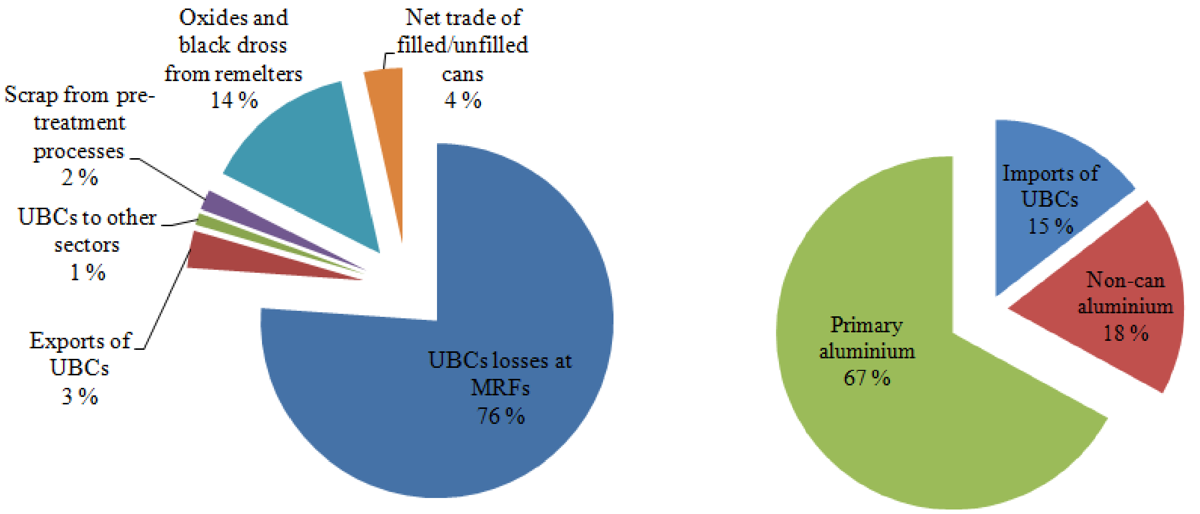

Figure 17: Share of aluminium flows across the system boundaries. 17a (left): Share of aluminium losses, 17b (right): Share of aluminium inflow

In the production of secondary ingot (ingot produced with scrap), 32% of primary aluminium and 19% of new scrap is used (figure 18a). The assumption made previously that 9 kilotonnes from the collected UBCs were sold to non-can use, and consequently 151 kilotonnes were used from non-can sectors for the production of new beverage cans, agree with the information from the Aluminum Association (2011). According to them, the beverage cans contains 49% post-consumer scrap (recycled UBCs + Non-can aluminium), and 19% post-industrial scrap (scrap from can manufacturing), which matches with the results shown below. There is still the need to identify if the source of the non-can aluminium is new or old scrap.

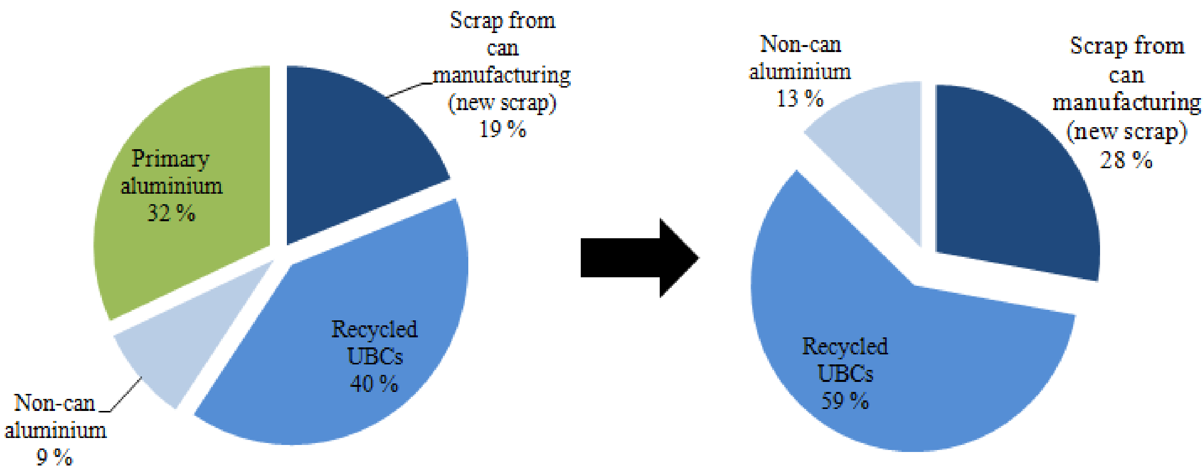

Figure 18: Composition of aluminium cans by source of aluminium (not considering internal scrap from mills). Figure 18a shows the recycled content including primary aluminium. Figure 18b shows the share of scrap in the composition of the can

From the total scrap used in the production of new cans (figure 18b), 28% is new scrap from manufacturing processes. It is important to mention that the results from figure 18b were considering the definition of recycled content by the Aluminum Association, and therefore internal scrap generated in the can sheet production was not considered. This has a significant impact on the amount and share of scrap use. If the internal scrap from mills is considered, the total scrap from production would contribute with more than 50% of the total recycled content, getting closer to the results indicated by Liu *et al.*, (2011) for the source of aluminium in aluminium sector in the USA.

3.1.1 Scenarios development for the static model

3.1.1.1 Increasing the cans recovery rate (CR)

If no trade (imports/exports) of aluminium is considered, and all the UBCs are used in a close-loop production, then reaching the 100% recycling rate would reduce the use of primary and non-can aluminium. Figure 19 depicts the assumptions for this scenario with data from 2010. Because of production losses, aluminium must be added to the system. The system losses represent around 10% of the total metal requirement to produce cans. That means that 90% would be the maximum system efficiency if the production processes are not improved. As it will be explained later in section 3.2.3.1 and 4.2, it is more likely that primary aluminium (instead of non-can aluminium scrap) is used to replace aluminium losses when a high recycling rate is reached, because of the difficulties to control the alloying elements concentrations at high recycling rates.

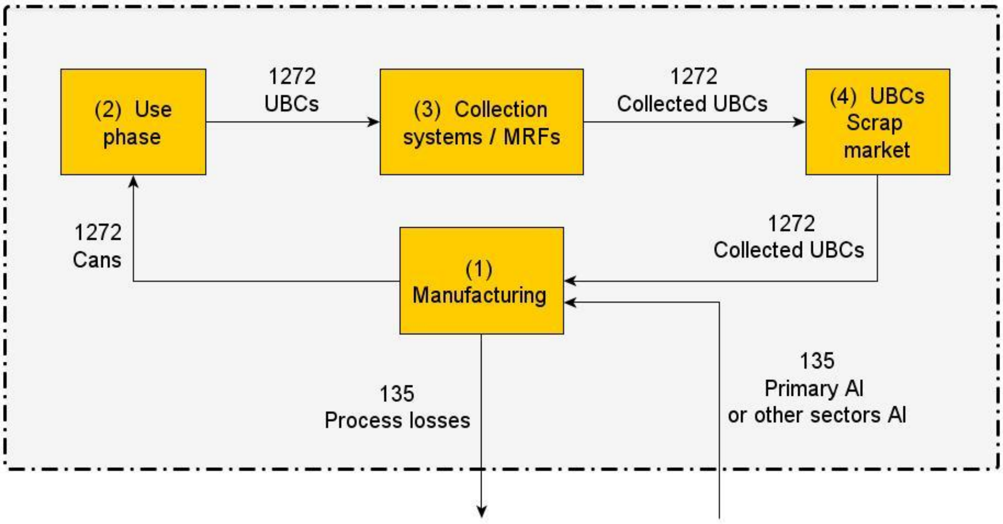

Figure 19: Can-to-can simplified static system, without trade and without non-can use for UBCs (in kilotonnes)

Even though 10% are the total material losses across the system boundaries, the production losses are larger. Considering scrap pre-treatment, remelting, can sheet production and can manufacturing, the total production efficiency would be:

$$\eta_{total\ prod.} = \eta_{Scrap\ pre-treatment} * \eta_{remelting} * \eta_{can\ sheet\ prod.} * \eta_{Can\ man.}$$

$$\eta_{total\ prod.} = 0.99 * 0.95 * 0.72 * 0.79 = 0.54 = 54\%$$

The total production processes have therefore a yield of 54%. There is a significant difference between the material efficiency and the process efficiency, showing that the level of disaggregation is important if the quantification of energy use and GHG is studied. Because of these production inefficiencies, additional energy is used in the production processes, thus increasing generation and emissions of GHG.

3.2 The dynamic model – Accumulation of alloying elements

3.2.1 Concentration of alloying elements in the body and lid

The typical concentration of alloying elements in the body and lid for the quantification of the system was taken from the work by Yoshida & Baba (2010) and presented in table 3. Even though the composition reflects the requirement for production of cans in Japan, the data do not differ considerably from other sources, such as Doutre (2011) for the North American aluminium can industry. The advantage of using the data from Yoshida & Baba is the use of Ti in the table, which is not found in other published studies.

Table 3: Typical composition of can parts and UBC recovery (wt %) (Yoshida & Baba, 2010)

part or category		Si	Fe	Cu	Mn	Mg	Ti
body material (actual value)		0.25	0.43	0.21	1.04	1.32	
end material (actual value)		0.09	0.25	0.04	0.30	4.42	
body + end (calculated)		0.22	0.40	0.18	0.87	2.02	
actual value (average) from UBC recovery		0.26	0.40	0.20	0.86	1.22	0.04
JIS limit of 3004	max.	0.30	0.7	0.25	1.5	1.3	0.10
	min.				1.0	0.8	

Table 3 shows the concentration of alloying elements in the body and lid (end), as well as the calculated and the actual concentrations in the recovered UBCs. It shows that from all of these elements, Mg can be removed by demmaging and therefore the actual concentration in the UBCs is lower than the calculated. Si, Cu and Ti are alloying elements, which actual concentrations are higher than those calculated by Yoshida. Mn has a considerable concentration reduction in the new body with regard to primary aluminium. The same trend for Si, Cu and Mn is shown in the work from Hatayama *et al.* (2007) in figure 20.

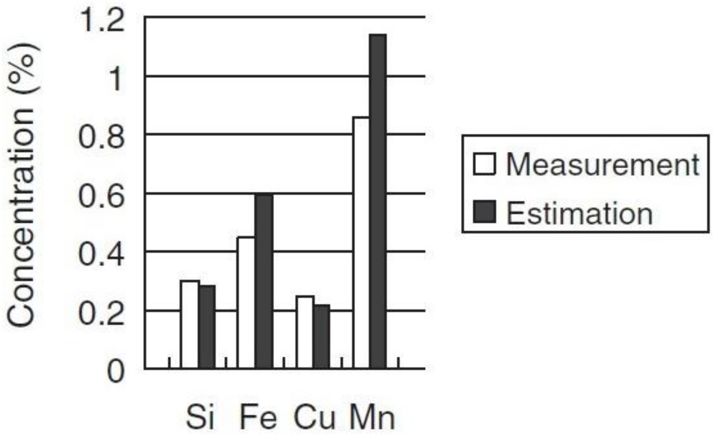

Figure 20: Comparison of measured and estimated concentrations for Si, Fe, Cu and Mn (Hatayama *et al.*, 2007)

Hatayama estimated the concentration of Si, Fe, Cu and Mn and compared them against the measured ones. In general the estimated and the measured concentrations keep a good correlation, but Si and Cu have slightly higher measured concentration, following the same trend as the data from Yoshida.

3.2.2 Accumulation of alloying elements in the body with no impurities inflow

It is possible to calculate the concentration in the new body (C_{23}) after the system has reached the steady state. For illustration purpouses a recycling rate of 58% was chosen (Recycling rate according to CMI) as the current recycling rate. Table 4 shows the concentrations when the steady state is reached, for both the new body (C_{23}), calculated with equation 3, and the collected UBCs (C_{34}), calculated with equation 2.

Table 4: Concentration of alloying elements at a steady state for the dynamic model for a recycling rate of 58% (wt %) [1]

Concentration		Si	Fe	Cu	Mn	Ti_1
C01	Primary Al concentration for Body	0.25 %	0.43 %	0.21 %	1.04 %	0.00 %
C02	Primary Al concentration for Lid	0.09 %	0.25 %	0.04 %	0.30 %	0.10 %
C34	Collected UBCs concentration	0.19 %	0.36 %	0.14 %	0.75 %	0.04 %
C23	New body concentration	0.21 %	0.38 %	0.17 %	0.85 %	0.03 %

In the hypothetical scenario of no impurities inflow ($\gamma = 0$), the new body will have lower concentration of Fe, Si, Mn, and Cu, because the concentrations of these alloying elements in the lid are lower than in the body. In this case the lid acts as a diluting material.

Ti and Mg exemplify a separate case. Concentrations of Ti and Mg in the lid are higher than in the body. For this reason, Ti and Mg in the new body will accumulate after each recycling loop. However, Mg is thermochemically removable by oxidation and fluxing during the remelting process, and nowadays does not constitute a major quality issue. The downside of removing Mg is the loss of this costly alloying element, which cannot be reused. Titanium on the other hand is not thermochemically removable, and the current method to control its concentration is by dilution with primary aluminium during the remelting process.

Figure 21 shows the accumulation of alloying elements in the new body after each can-to-can recycling loop. Mg and Mn are two elements that are out of tolerance according to these results. However, the concentration of Mg can be reduced by demmaging. The concentration of Mn is below the tolerance, which does not represent a problem, because additional Mn can be added to keep it within tolerance.

[1] To calculate the concentration of titanium for this case Ti_1, it was assumed that the concentration in the lid was equal to its upper concentration limit.

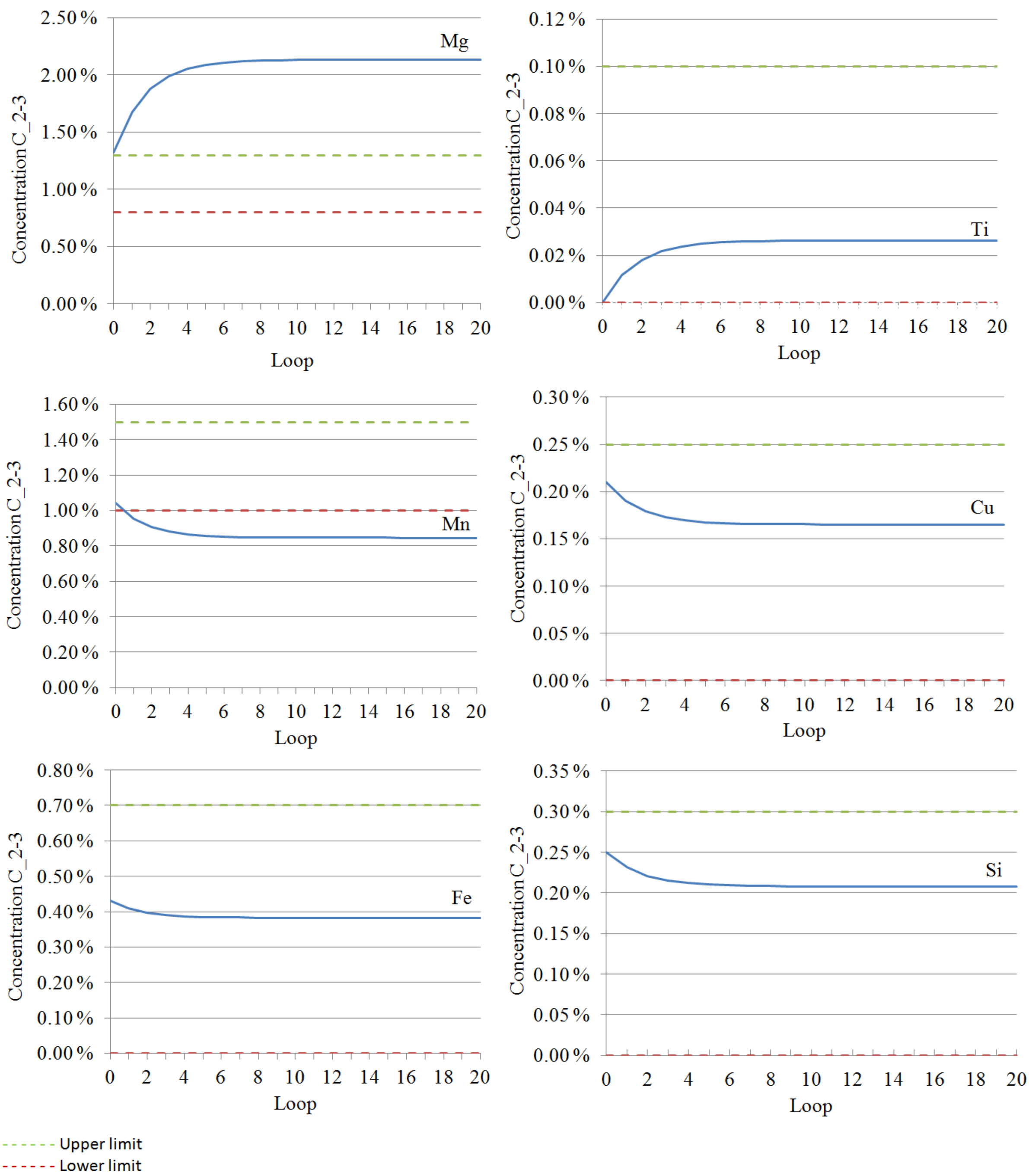

Figure 21: Accumulation of alloying elements in a can-to-can recycling, no impurities inflow, 58% recycling rate

The system reaches the steady state (plateau) when the mass inflow equals to the mass outflow of the same alloying element across the system boundaries. Given the example of titanium (figure 22) where the lid has a higher concentration of titanium than the body, the concentration of Ti in the new body will increase after each recycling loop. However, the amount of titanium that the body will uptake from the lid will be less after each loop. This can be easier explained by referring to equation No. 3. Using this equation for a 3 loop (n=3) as example, the equation results in:

$$C_{23}^{3} = \theta * (1 + CR + CR^2) + CR^3 * C_{prim}$$

Θ is a constant. Because CR < 1, then CR > CR^2 > CR^3. Therefore, after each can-to-can recycling loop, the relative concentration growth is smaller than in the previous loop. Thus, after a certain number of recycling loops the curve will not show a significant growth, and it can be considered that $CR^n \approx CR^{n-1}$ (plateau level). This is a steady state and no further accumulation of the alloying element in the system occur. It is important to mention that the steady state (plateau level) could be reached when the concentration is already out of tolerance. In the example below, the inflow of Ti into the system is 0.00229g and the outflow of Ti is also 0.00229g, meaning that the steady state was reached.

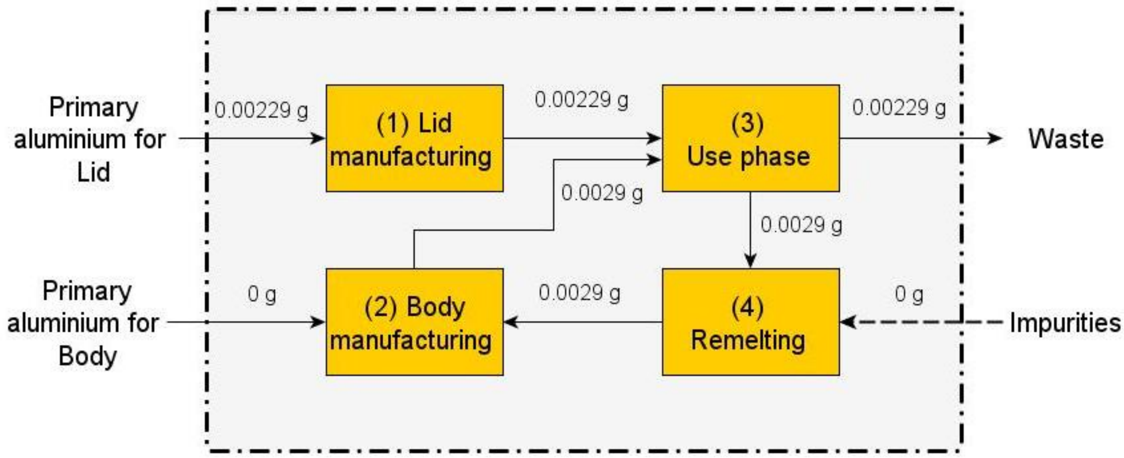

Figure 22: Example of Ti flows for when the steady state is reached, no impurities inflow, 58% recycling rate

Impurities such as Si or Fe could potentially have a higher impact in the recyclability of the UBCs. Si may enter the system through external factors, such as dirtiness or use of cast aluminium. Fe may enter the system through the wear and tear of production equipment (Green & Skillingberg, 2006). Concentration of Ti may grow because this chemical element is present in the paint, which is used for the external decoration of the cans. Ti is thereby an interesting element to analyze.

3.2.2.1 Si in the system

Figure 23 shows the concentrations of Si in the new body (C_{23}) for different recycling rates when no impurities enter the system. It can be noticed that the higher the recycling rate, the lower the concentration of Si at a steady state. With a recycling rate of 50%, the concentration stabilizes at C_{23} = 0.22%, while at a recycling rate of 80%, it stabilizes at around C_{23} = 0.12%. It also takes more loops to reach the steady state at higher recycling rates. While at a recycling rate of 50% it takes only around 10 loops, it takes around 30 loops to reach the plateau level for a recycling rate of 80%.

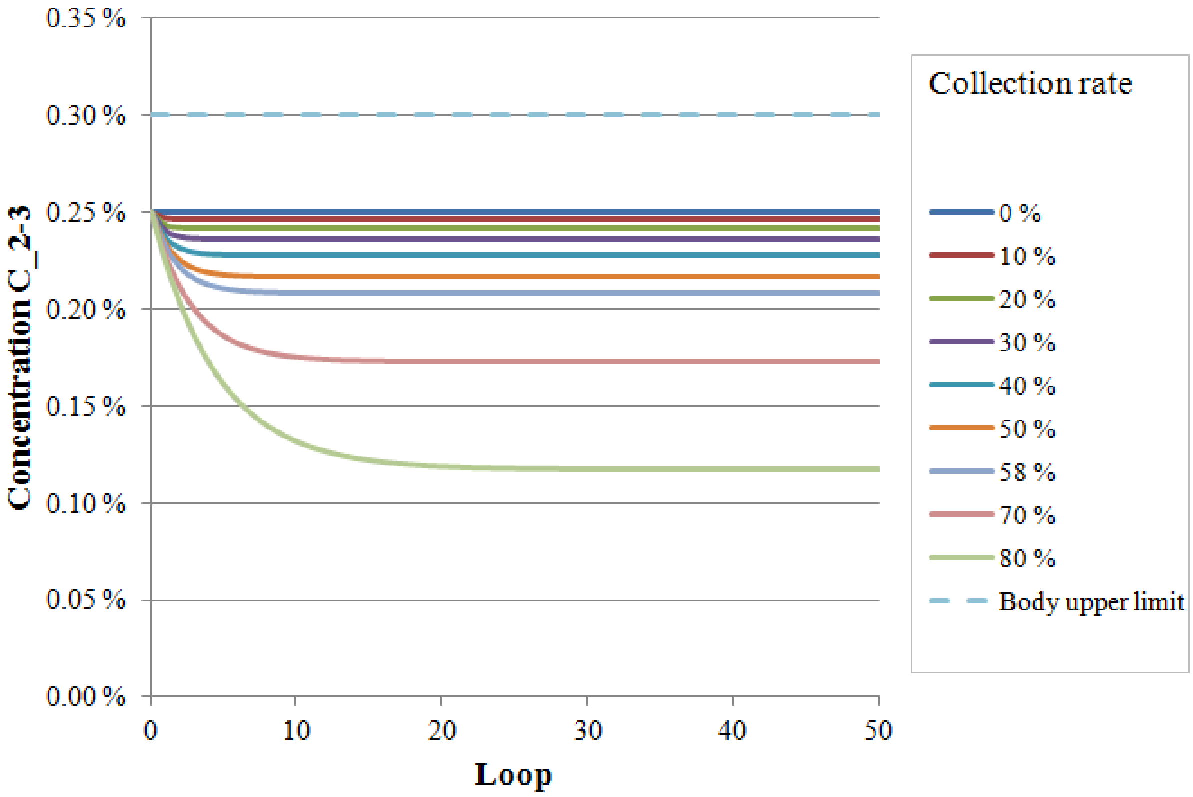

Figure 23: Concentration of Si in the body for different recycling rates, no impurities inflow

In practice the concentration of Si in the body is not expected to decrease, because of impurities entering the system. Compared with other alloying elements, there are more sources of Si in the whole aluminium cycle, increasing the likelihood of inflow of this element.

3.2.2.2 Titanium in the system

Figure 24 shows the concentration of titanium (Ti_1) in the body for different collection rates when no impurities enter the system. With the current recycling rate (of 58%) the system stabilizes at a concentration C_{23} of around 0.026%. When the CR increases up to 83%, then after around 40 recycling loops, the concentration of Ti in the body reaches its upper tolerance. With a recycling rate higher than 83%, the concentration of titanium exceeds its upper tolerance. Therefore, under the assumed conditions, it will not be possible to recycle more than 83% of the UBCs.

Ti is an interesting case to study because the cans are decorated with paint that might contain titanium (Rabah, 2003). Conversely, other elements such as Fe, Cu or Si are introduced unintentionally in some of the processes along the value chain. The concentration of Ti increases as the recycling rate increases. Moreover, increase of collection rate from 20 to 30% does not have the same impact on the concentration of titanium as when the collection rate increases from 70 to 80%.

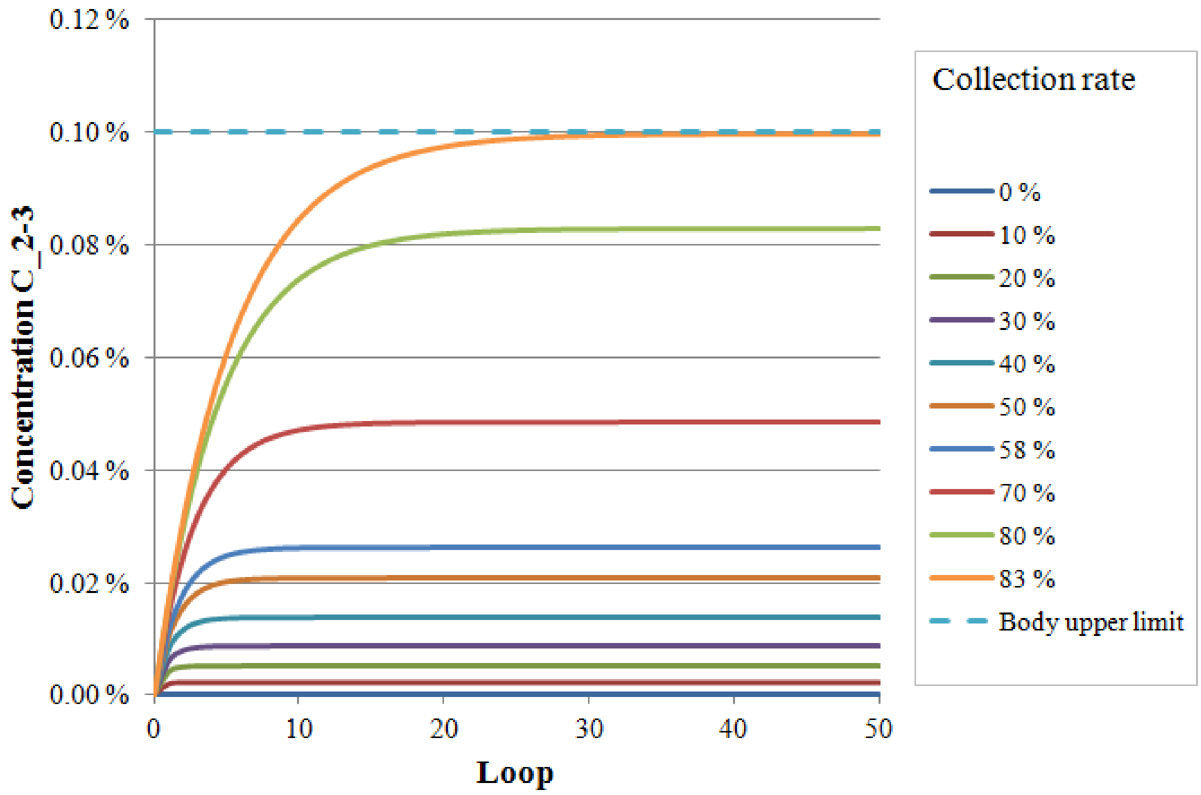

Figure 24: Concentration of Ti in the body for different recycling rates, no impurities inflow (for Ti_1)

3.2.3 Accumulation of alloying elements in the body with impurities inflow

3.2.3.1 Maximum inflow of impurities

Considering that the difference between the calculated and the measured concentration of alloying elements (C_{34}) in the UBCs from table 3 is because of the inflow of impurities into the system, the concentration of UBCs with impurities (C_{42}) can be calculated using equation 5, then:

$$\gamma = C_{42} - C_{34}$$

Assuming that γ remains constant after each recycling loop then:

$$\gamma = 0.26 - 0.22 = 0.04$$

This is a rough estimation of Si entering as impurity into the system. However, it is useful in order to visualize how this inflow will modify the trend of the curves from figure 23. The results are visualized in figure 25. A small inflow of impurities can have a large impact on the recyclability of aluminium. With γ = 0.04% it is clear how the trend of the concentration changes from reduction to accumulation. Moreover, at high recycling rates, the impurities would potentially limit the system to recycle more. As was mentioned before, γ = 0.04% is a rough estimation. Better quality of data is necessary to be safe on the results, but it is still interesting to visualize the influence of impurities.

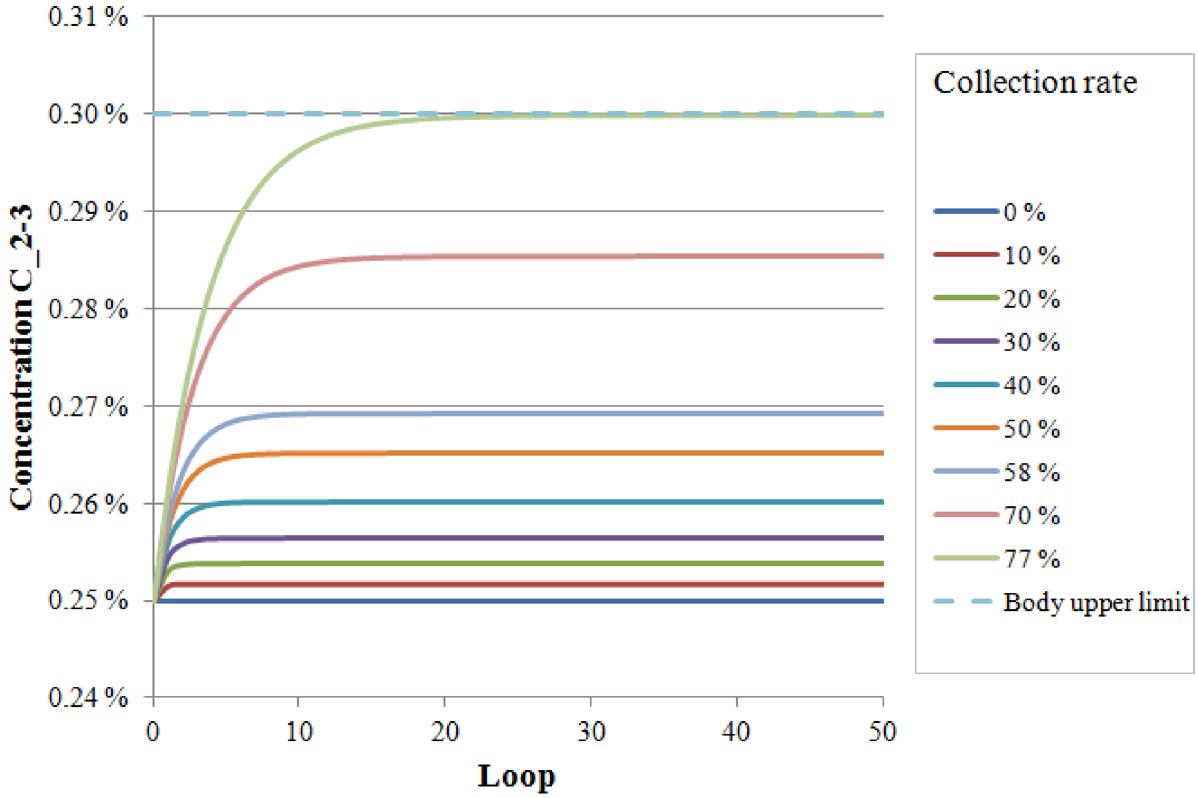

Figure 25: Concentration of Si in the body for different recycling rates, with impurities inflow

Lack of reliable data on impurities inflow is problematic for the estimation of the maximum recycling rate. However, it is possible to forecast the maximum inflow of impurities (γ) that the system can tolerate when the collection rate increases. Figure 26a shows the maximum concentration of impurities entering the system (γ), where γ is a percentage (in weight) of the alloying element mass in the collected UBCs (C_{34}), thus $A_{04} = A_{34} * \gamma$. The horizontal axis represents the collection rate (CR) and the vertical axis represents the maximum entry of impurities, γ. The figure shows γ for each of the studied alloying element. For example, with a CR = 50%, the maximum γ is 0.5% for Mn. In the case of Fe, with a CR = 40%, γ = 0.37%. Figure 26b shows the amplified results.

For CR > 82%, the model is not valid, because 82% is the body weight share from the total weight of the can. Currently UBCs are used to produce only the body. A collection rate above 82% would mean that the surplus of UBCs should be used for the lid production, not usual nowadays. The model quantifies the flow C_{23}, which gives the concentration of the new body stock and does not calculate the concentration in the lid. Therefore in figure 26 the model is not valid above this 82%. The model does not include the production yield, which in total accounts for around 10% of losses. Considering those 10% of production losses, a rough estimation of the maximum recycling rate would be:

$$CR_{max} = \frac{0.82}{(1-0.1)} = 0.91 = 91\%$$

Where 0.82 is the can body share. Beyond CR = 91% the surplus of UBCs would need to be sent to non-can sectors.

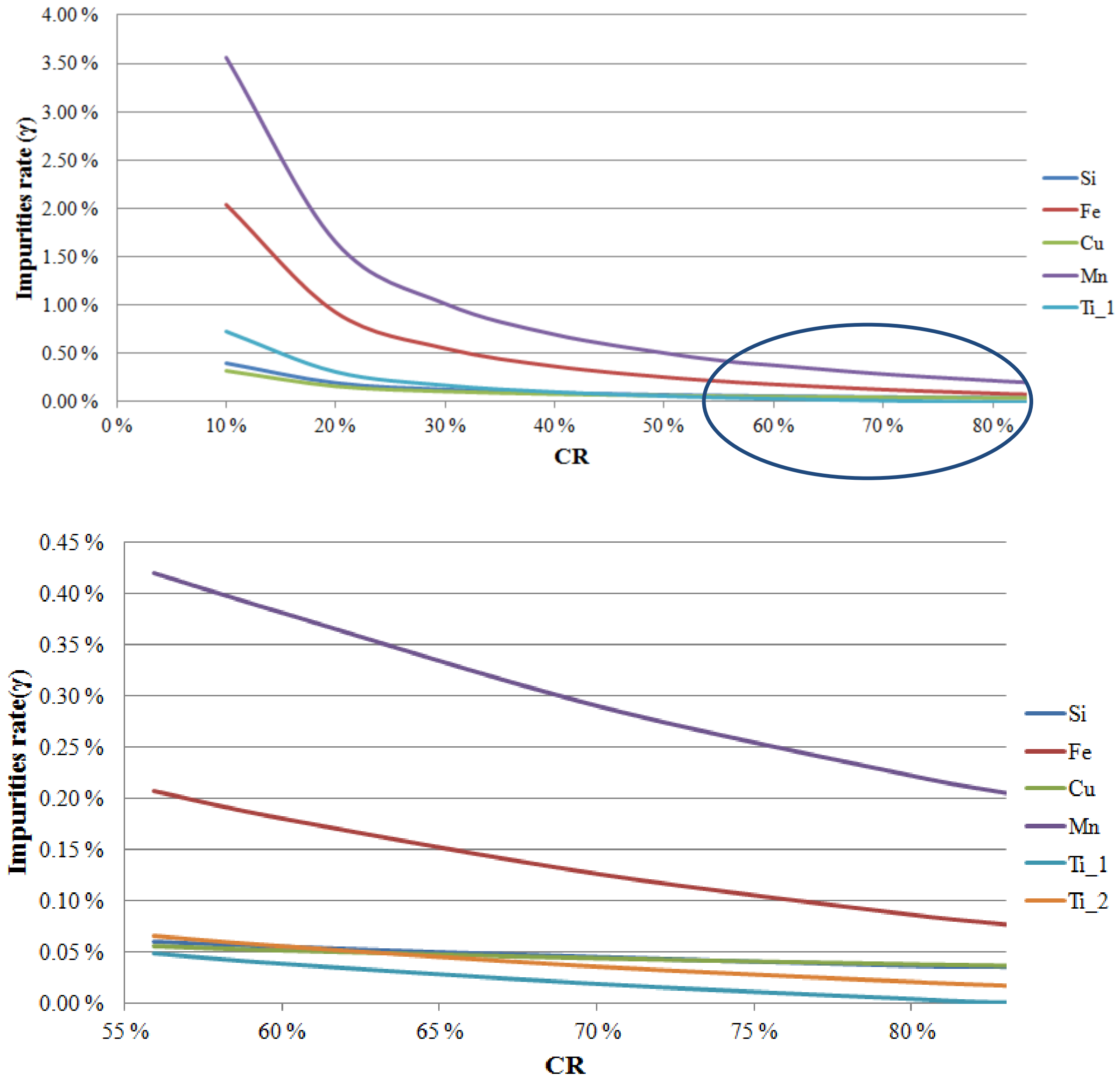

Figure 26: Maximum concentration of impurities inflow allow into the system depending on the recycling rate. The lower figure (26b) shows amplified concentration ratios between 55% and 82%

Two cases were developed for titanium. Ti_1 shows the curve for titanium considering a concentration of Ti in the lid equal to 0.1%, while for Ti_2 the concentration in the lid is 0%. In the first case (Ti_1), at CR = 83%, the system cannot accept more Ti into the system. Above 83% (not considering manufacturing losses) the concentration of Ti in the new body would constrain further recycling of UBCs, as it would exceed its upper tolerance (0.1%). On the second case (Ti_2), CR = 100% could be reached, but in practice this currently not possible due to the body share ratio of 82%. Therefore the maximum CR (not considering production losses) would be 82%.

Mn and Fe are two elements with a higher tolerance to impurities compared to Ti, Cu or Si. As was seen before, Mn might not enter to the system as impurities, and contrarily additional Mn may be needed. Cu and Si are more sensitive to the inflow as impurities compared to Fe. At a lower recovery rate, the critical elements to control would be Cu, Si and Ti in that order, while at high CR, the critical elements to control would be Ti, Si and Cu in that order. At high CR, there will be an increased difficulty to control the concentration levels. Ti would probably represent a challenge for the remelting companies when higher collection rates are reached.

3.3 Sensitivity analysis

The previous results showed that titanium will be a limiting alloy at high recycling rates. Therefore it is interesting to see how different concentrations of Ti in the lid affect the recyclability. Figure 27 shows the relation between the impurities entering the system (γ = 0 to 0.1 wt %) against the maximum collection rate (CR = 0 to 100%), for different titanium concentration in the lid (C_{lid} = 0 to 0.1 wt % of titanium). The graph shows that when more impurities enter the system, fewer UBCs can be recycled. For example, for impurities inflow γ = 0.1%, the maximum recycling rate ranges between 40 to 45%.

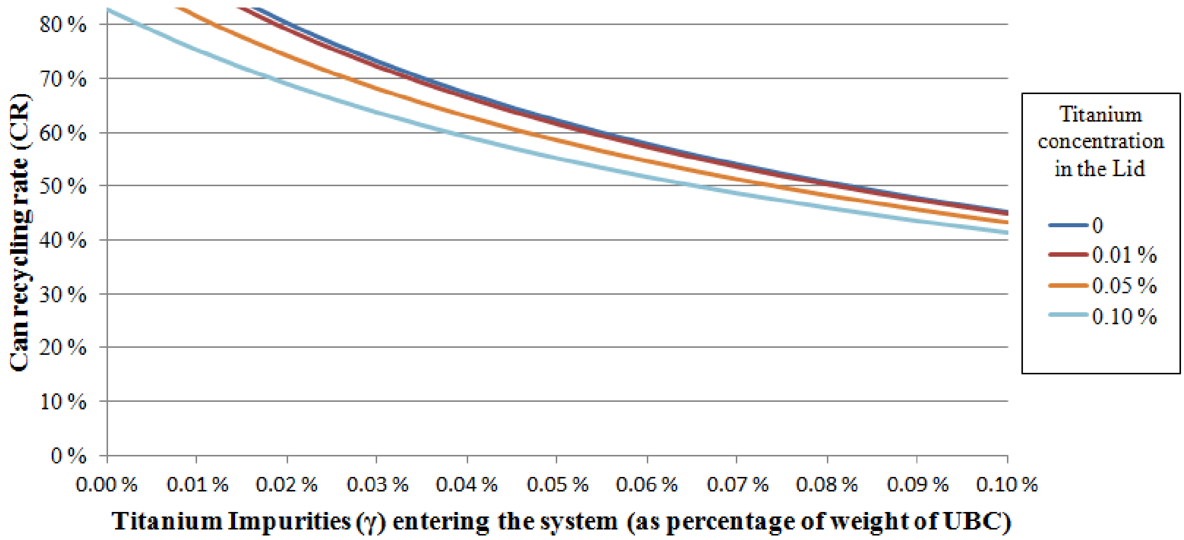

Figure 27: Maximum recycling rate depending on the concentration of Ti in the lid and impurities entering the system

It can be noticed that in the case of Ti, the impurities (γ) restrict more the cans recycling than the Ti content in the lid (C_{lid}). For example, increase in the impurities from 0.03% to 0.04% ($\Delta\gamma$ = 0.01%) entails to a reduction in the recycling rate of around ΔCR = 6%. On the other hand an increase of Ti concentration in the lid, from C_{lid} = 0 to 0.01% (ΔC_{lid} = 0.01%), for a constant value of impurities γ = 0.03%, leads to a reduction in the recycling rate of only ΔCR = 1%. Even more, the higher the inflow of impurities, relatively less effect has the concentration of Ti in the lid. Therefore an effective control of the decoating process will be needed to reach high recycling rates.

4. Discussion

4.1 Methodological reflections

A static model was developed to quantify the flows of aluminium in the USA. Accumulation of stocks was not considered in the model, owing to the short life-span of beverage cans. The flows were quantified with mass balance equations and transfer coefficients, and the system boundaries were limited to the processes entailed in can recycling. The manufacturing yields were obtained directly from PE Americas (2010), who worked with data provided by the aluminium industry in the USA. 90% of metal yield in the manufacturing process and 10% of industrial scraps were the results from the static system, close to the yield rate of industrial scraps given in the work of Hatayama *et al.* (2007), of 15%. Total post-consumer UBCs and collected UBCs data was obtained from EPA (2011). The amount of collected UBCs from the MRFs is consistent with the data provided by CMI (2012). A pre-consumer beverage can trade data, including filled and unfilled cans was available, but the classification of this data was not suitable for the quantification of the system. Consequently, trade of pre-consumer beverage cans was calculated with the difference between post-consumer UBCs scrap and cans production data.

One of the largest uncertainties in the static model was the flow of UBCs to non-can sectors. The assumptions made to quantify this flow apparently generated results that agree with the results from publications made by the Aluminum Association, but better data should be found regarding this flow. The assumption made for the UBCs flow to non-can sectors affects the inflow of aluminium from non-can sectors used in the can sector. When a higher flow of UBCs is sold to non-can sectors, then more aluminium from non-can sectors is used in the production of new cans. In 2010, the estimated inflow of aluminium from non-can sectors was relatively large (9% of the total inflow of aluminium to the system), which could have critical influence in the concentration of alloying elements in the recycled aluminium, depending on the composition of this scrap. The source of this scrap is needed to track, in order to calculate the concentration of alloying elements in the aluminium entering the system. Additionally, it would be necessary to identify if the source of the non-can aluminium is pre- or post-consumer scrap. Pre-consumer scrap would normally be better classified according to aluminium alloys than post-consumer scrap, which may be composed of different alloys.

The proposed system definition can be improved by identifying better where the new and old scrap from industry is sold to. Because of the different scrap operators, such as large integrated aluminum producers, independent manufacturers of wrought products (shaped for end product use), or producers of secondary-specification alloy ingot (Plunkert, 2006), it is still not certain where the new and old scrap from the can manufacturing facilities will end up. In the system proposed in this study, only secondary remelters and internal remelters were included, where the secondary remelters could eventually sell the produced ingots to non-can scrap sectors, meaning additional loss of metal.

The static model provides a good overview of the system flows for the aluminium can recycling system. Some data must be improved, but the assumptions made in this study are sufficient to understand the behavior and the limitations of the system. Many factors affect the can-to-can recyclability, and one of those major factors is the loss of cans into landfills or incineration facilities, as well as trade. A larger outflow of collected UBCs entails a larger inflow of non-can UBCs and primary aluminium.

A dynamic model was developed to analyze the accumulation of alloying elements in the system. This model was more data independent than the static model, but information about the concentration of alloying elements was necessary. Data on the alloy composition can be obtained more readily from Japanese publications than from the aluminium industry in the USA. Therefore data from Yoshida & Baba (2010) was used to quantify the accumulation of alloying elements, even though not the latest in the industry. There is a lack of information about the inflow of impurities in the can sector. Because a real estimation of the maximum recycling rate achievable is constrained by the inflow of impurities into the system, better impurities data is required to simulate the system.

One of the limitations of the dynamic model is that it calculates the concentration of alloying elements in the new body, and therefore the model can be used only until a CR of 82%, which is the body weight share. Beyond that 82%, the model cannot be used. The dynamic model can estimate the concentrations of alloying elements, and it can show how impurities and alloying elements will constrain the recyclability of UBCs in the future. The dynamic model does not include trade of aluminium with other regions or aluminium sectors, as it is intended to basically show the effect of impurities in the recyclability of cans.

4.2 Future strategies and policy relevance

This study shows that the recycling rate of UBCs has the potential to grow further. Reaching the recycling rate of 75% in the near-term set by the Aluminum Association (The Aluminum Association, 2011) would actually not require technology development. The definition of recycling rate that the Aluminum Association publishes includes imports and exports of UBCs. This gives a distorted impression of the recycled metal. With the definition of UBCs recycling rate from the Aluminum Association, it would just require increasing the imports of UBCs to reach this target, shrugging off the need of better collection systems and UBCs supply chain; and imports might have a large importance in the future, because the USA has fallen from being the second producer of alumina (after Australia) in 1980, to produce only 5.1% of world production, as well as from being the No. 1 producer of aluminium to be the third (Buffington, 2012).

The largest losses of UBCs in the USA are due to inappropriate collection systems in combination with the allocation of the UBCs to non-can sectors, preventing a close-loop system. If those two issues are addressed, following the proposal of many other studies, then when a high collection and recycling rate is reached, the alloying elements will represent the next technological challenge to this sector. A stricter compositional control will be required. This control should encompass all the processes in the system, including production, scrap management and pre-treatment processes in order to reduce the entry of impurities.

Assuming that 75% UBCs recycling rate is the objective, but using the definition from CRI and EPA, the steps to reach a close-loop, and even higher recycling rates, visualized in figure 28, can be follow.

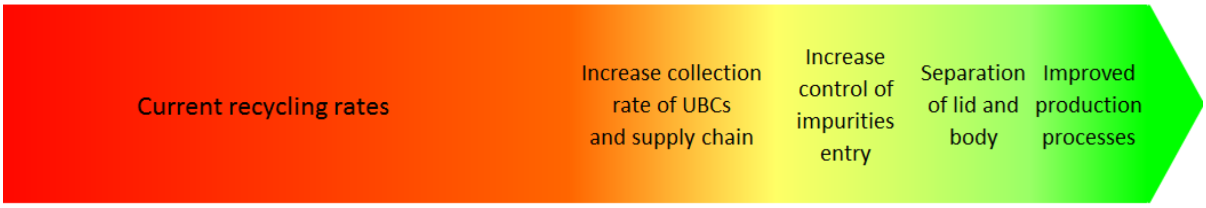

Figure 28: Steps to reach a higher recycling rate in a close-loop, can-to-can system

The steps to reach a higher recycling rate do not need to be strictly in that order, and some (if not all) of the steps can be followed simultaneously to reach the goal. The current recycling rate is around 50% (CRI and EPA definition). The next step will be to increase the UBCs collection rate and supply chain, which would allow the system to recycle above 90% of the UBCs (counting also the production losses), which is the long objective set by the Aluminum Association (The Aluminum Association, 2011). Consumer behavior, recycling infrastructure and socio-economic context will affect the collection of old scrap (Liu *et al.*, 2010), while integration of the secondary scrap market with the aluminium producers would improve a can-to-can system (Buffington, 2012).

High levels or recycling rates need to go hand in hand with a better control over impurities. The higher the recycling rate, the harder it would be for the remelters to control the alloying elements concentrations. Without control over the impurities it is doubtful to reach a recycling rate of 90%. Nowadays input of aluminium from non-can sectors are blended together with the UBCs (Doutre, 2011), which might contain high concentration of Si such as parts of shredded castings, or other sources. High level of impurities in the scrapped aluminium would push the system to sell the UBCs to other sectors, increasing the amount of downgraded aluminium. In order to avoid these sources of impurities, better material quality should be demanded, meaning better control on the UBCs cleanliness to avoid elements such as Si, improved removal of iron, including stainless steel that could be introduced in the use phase. Ti is deliberately introduced in the can system for decoration purposes, which can potentially limit the recycling of UBCs. Therefore it will be necessary to reach a high decoating efficiency. At high recycling rates, scrap from other sectors would require being 100% reliable or even avoided.

If the previous challenges are addressed, the next step will be to separate the UBCs into bodies and lids, so that the scrapped bodies are sent to the body remelters, and the scrapped lids to the lid remelters. The lack of separation is not a concern for the UBCs remelters nowadays, because with the current recycling rates the blending of alloys from the lid and body is still suitable for the body manufacture. However, with recycling rates beyond 90%, the surplus of UBCs will not find use in the can sector. With this additional separation process, 100% of the collected UBCs would be possible to recycle.

Even after the separation of the lid and body, primary aluminium would still be needed in order to compensate the production losses. Improvement in production processes will be necessary to produce cans with the highest recycled content and the minimum use of primary aluminium. By reducing the use of primary aluminium economical and environmental costs are saved. Each ton of recycled aluminium saves 24 barrels of crude oil equivalent energy, 15 tons of water, 9 tons of CO2-eq, 2.5 tons of solid waste, among other benefits (The Aluminum Association, 2011).

Two additional strategies to increase the recyclability are mentioned and studied by several authors. The first one is the creation of a uni-alloy for the manufacture of the cans. The idea is to have an average weighted composition that could fit the requirements for both the lid and body. The concept was first developed in late 1980's, but due to economic and commercial reasons, it have had limited application so far (Das, 2006). It would be interesting to know if it would represent a better environmental performance to continue reducing the weight of the can, or instead to design the cans with a uni-alloy aluminium. As the can industry today has being developing manufacturing processes to reduce the weight of the can, changing to uni-alloy aluminium could change dramatically the path for future development. Currently the body has a very light wall thickness comparing to the lid, which has to be stronger to resist the pressure of the beverage. Changing to uni-alloy would mean to change the thickness of the body, most plausible to a thicker one, thus increasing the total weight of the can. An increase in the total weight of the can will mean more metal requirement, thus increased amount of primary aluminium required initially. Furthermore, a heavier weight of the can would represent additional fuel consumption for transportation of the cans. However, the development of the uni-alloy would mean a higher recycled content in the aluminium can, and thus less use of primary aluminium when the recycling loop is closed.

The second strategy is to extract the alloying elements during the remelting process. The typical refining method to remove impurities in metals is by oxidation. This refining technique generates loss of aluminium, because aluminium is oxidized before the impurities, and lost to slag or dross (Nakajima *et al.*, 2010). This can be illustrated in figure 29, which shows the Gibbs free energy change as a function of temperature for different metals (Gaustad *et al.*, 2012). The oxidation reaction of aluminium is represented by the black line. It can be seen that most of the equilibrium lines have higher Gibbs free energy (above) than aluminium. Only Mg and Ca are oxidized before aluminium.

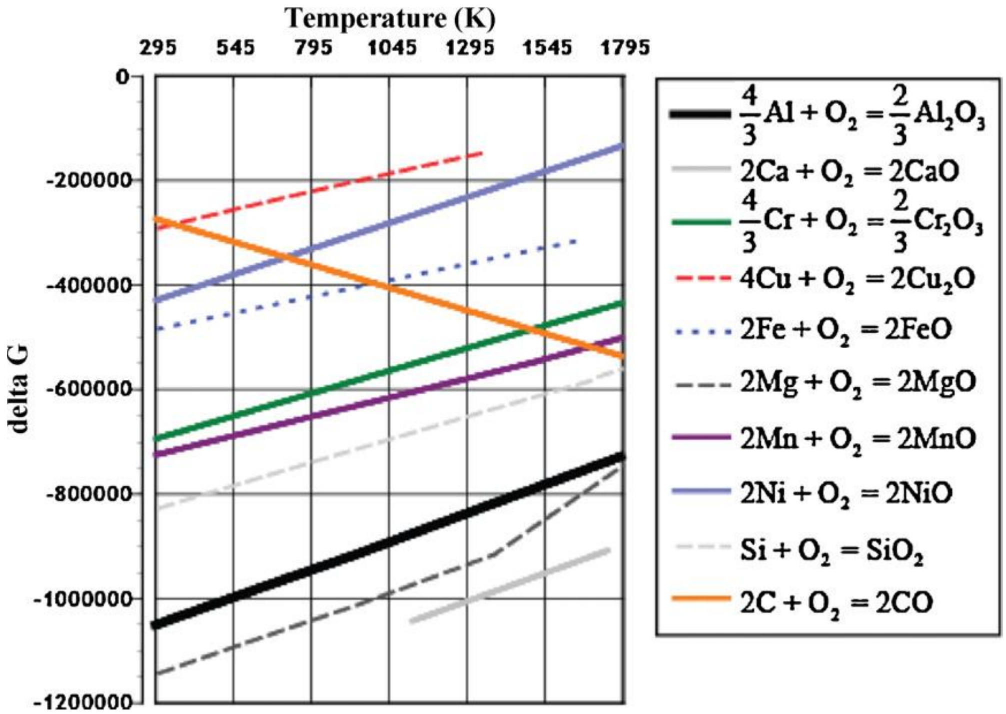

Figure 29: Ellingham diagram (Gaustad *et al.*, 2012)

Impurities such as Ca, Sr, Na, Mg and Li can be removed also by fluxing (adding inorganic compounds, chemicals or gasses to the melt). The downside of this operation is that large amount of the flux may be required to achieve sufficient reactions, and some gasses such as chlorine and fluorine produce toxic gasses. High purity aluminum can be obtained with the Hoopes process. However, this technique is even more energy intensive (17-18 kWh/kg) than the production of primary aluminium. Other techniques to upgrade aluminum such as distillation, unidirectional solidification, or fractional crystallization, may remove only certain chemical elements, or are still in development (Gaustad *et al.*, 2012).

As long as aluminium diversity of applications continues growing, in applications where highly alloyed aluminium does not represent a problem for the manufacture and product itself, UBCs will still be used in other sectors. Downgrading under this scenario would not represent a major issue for the aluminium industry unless the growth of applications starts decreasing its speed. In the scenario where new applications are not appearing, the scrap dealers would start having problems allocating the UBCs. In this scenario, the development of the technology to separate the parts of the UBCs will be considered. Even though a perfect close loop, can-to-can recycling is still far, due to the growing aluminium applications, it is useful to recognize the future limitations of can-to-can recycling, so that the stakeholders involved in the beverage cans recycling are aware of their future needs.

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