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Component- and Alloy-Specific Modeling for Evaluating Aluminum Recycling Strategies for Vehicles

ROJA MODARESI,[1,2] AMUND N. LØVIK,[1,3] and DANIEL B. MÜLLER[1,4]

1.—Industrial Ecology Programme (IndEcol), Department of Energy and Process Engineering (EPT), Norwegian University of Science and Technology (NTNU), 7491 Trondheim, Norway. 2.—e-mail: roja.modaresi@ntnu.no. 3.—e-mail: amund.lovik@ntnu.no. 4.—e-mail: daniel.mueller@ntnu.no

Previous studies indicated that the availability of mixed shredded aluminum scrap from end-of-life vehicles (ELV) is likely to surpass the capacity of secondary castings to absorb this type of scrap, which could lead to a scrap surplus unless suitable interventions can be identified and implemented. However, there is a lack of studies analyzing potential solutions to this problem, among others, because of a lack of component- and alloy-specific information in the models. In this study, we developed a dynamic model of aluminum in the global vehicle stock (distinguishing 5 car segments, 14 components, and 7 alloy groups). The forecasts made up to the year 2050 for the demand for vehicle components and alloy groups, for the scrap supply from discarded vehicles, and for the effects of different ELV management options. Furthermore, we used a source-sink diagram to identify alloys that could potentially serve as alternative sinks for the growing scrap supply. Dismantling the relevant components could remove up to two-thirds of the aluminum from the ELV stream. However, the use of these components for alloy-specific recycling is currently limited because of the complex composition of components (mixed material design and applied joining techniques), as well as provisions that practically prevent the production of safety-relevant cast parts from scrap. In addition, dismantling is more difficult for components that are currently penetrating rapidly. Therefore, advanced alloy sorting seems to be a crucial step that needs to be developed over the coming years to avoid a future scrap surplus and prevent negative energy use and emission consequences.

INTRODUCTION

Aluminum is used in the form of many different alloys with variable concentrations of alloying elements, such as copper, manganese, magnesium, silicon, iron, and zinc. The high and increasing complexity of alloys presents recycling challenges, particularly because these alloying elements, with the exception of magnesium,[1] cannot be removed cost effectively through refining due to thermodynamic constraints.[2–4] Thus, the aluminum scrap that is recovered as mixed fractions (e.g., shredded products that contain various alloys and other materials) typically cannot be used to produce alloys contained in these products. Thus far, the aluminum industry has been able to recycle a wide variety of alloys primarily by increasing the alloying element levels of the material to create foundry cast alloys, which have a higher tolerance for impurities but often require either additional alloying elements or the dilution of scrap with clean primary material to attain the necessary material qualities.[1,4,5] However, there are clear indications that blending and dilution are becoming less effective as the amount of the old scrap supply is increasing faster than demand for secondary casting applications that can absorb mixed scrap, resulting in a potential surplus of low-quality scrap.[6–10]

To make use of all the aluminum scrap in the future and thus benefit from the potential energy and emission savings, it is therefore of utmost importance to identify alternative recycling strategies that are better suited to address the growing complexity of aluminum products. Of particular

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relevance is the recycling of automotive applications because (I) they account for a broad range of different alloys, (II) they represent already today the largest market for secondary aluminum castings, and (III) they are responsible for a very strong increase in wrought aluminum demand. According to our previous study,[8] a scrap surplus can be avoided only by separating the wrought and cast aluminum fractions and using wrought scrap as raw material for rolling and extrusion alloys. The model used in that study allows for robust identification of the problem; however, its high aggregation level limits the evaluation of practical solutions because of the multitude of aluminum-containing components in automobiles and their highly complex alloys. Another group has developed a dynamic optimization model for end-of-life vehicles (ELV) recycling and demonstrated that product design by particle size reduction and liberation of material during shredding plays an important role in the composition and quality of recycling streams,[11,12] whereas others have investigated designs for recycling and optimization of refining and recycling processes.[1,2,13,14] Because automotive aluminum usage is expected to grow more rapidly in components consisting of wrought aluminum,[9,13,15–18] it is important to identify components with wrought alloys or develop new "recycling friendly" alloys for these applications that could serve as intermediate reservoirs (sink alloys); such small-scale recycling practices have already begun. For example, Nissan collects and recycles aluminum wheels to construct suspension part and has developed pilot technology for bumper-to-bumper recycling.[19]

Although all the aforementioned models provide important insights into the effectiveness of strategies both technically and economically, they cannot forecast simultaneously scrap supply and aluminum demand both on a component and alloy basis, which is necessary to test whether the separated scrap fractions could be used in new vehicles. Consequently, the models cannot identify alternative strategies by which to avoid or delay filling the bottom reservoir of secondary cast alloys, such as closing-alloy cycles or recycling toward intermediate reservoirs that may have the capacity to use different types of wrought alloy scrap. The source-sink diagram (Fig. 1) illustrates the potential for the typical automobile alloys to act as scrap sinks from several source alloys using the maximum recycled content as an indicator. As indicated by the white diagonal in the figure, all alloy scrap can be recycled to their original alloy ("closed-alloy cycle") with minimal need for the dilution or addition of alloying elements, but potential sink alloys are limited.

In this study, we developed a component-alloy model of the global vehicle stock. The component-alloy model is used to forecast the demand for sink alloys and the supply of source alloys within a vehicle system, and the source-sink alloy diagram (Fig. 1) is used to identify potential sink alloys that

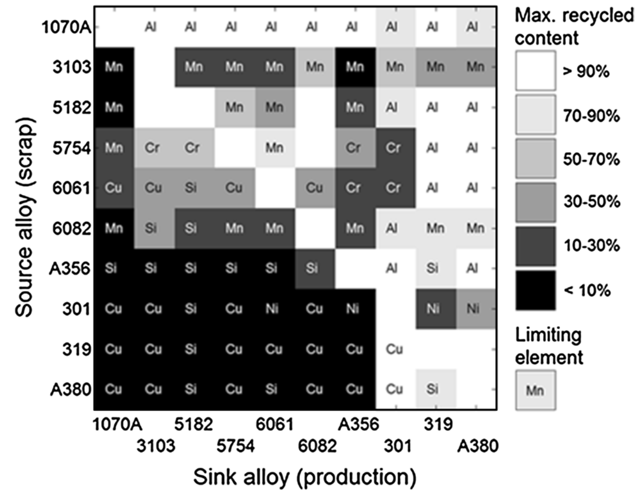

Fig. 1. Options and constraints for recycling paths of typical automotive aluminum alloys due to alloying elements. The different colors indicate the percentage of a source alloy (scrap) that could be used in the production of a sink alloy. There is a clear potential in recycling wrought alloys (4-digit names) into cast alloys, such as alloys 319 and A380, shown by the lighter shades to the right. Another potential sink alloy is alloy 6082, which could absorb a mixture of typical wrought alloys. The limiting element is shown inside each square. Magnesium is not considered because it can be removed by chlorination. Calculations are based on compositional limits from industry standards.[20,21]

could serve as intermediate reservoirs. Furthermore, the model is used to assess the influence of different ELV strategies (dismantling versus alloy sorting) on scrap composition. This study is an initiation and development based on a European project for estimating aluminum alloys and components in ELVs for European Aluminium Association (EAA) and International Aluminium Institute (IAI).

We address the following questions: How is the changing use of aluminum in cars components expected to influence alloy demand and scrap composition in the next decades on a global scale? What are the most promising intermediate reservoirs (sink alloys), and which alloys are most suitable as raw material sources? In which components can these source alloys be found, and what are the prospects of obtaining these source alloys through dismantling? What changes can be made from the system perspective with respect to ELV management practices to increase recycling in the future?

METHODOLOGY

System Definition

Figure 2 illustrates the global aluminum cycle related to passenger cars. The system includes passenger car production, use, and ELV management. Passenger cars are broken down into 5 car segments (S1–S5), 14 car components (C1–C14), and 7 alloy groups (A1–A7). Cars enter the use phase and provide services to society during their lifetime. After the use phase, the cars collected for

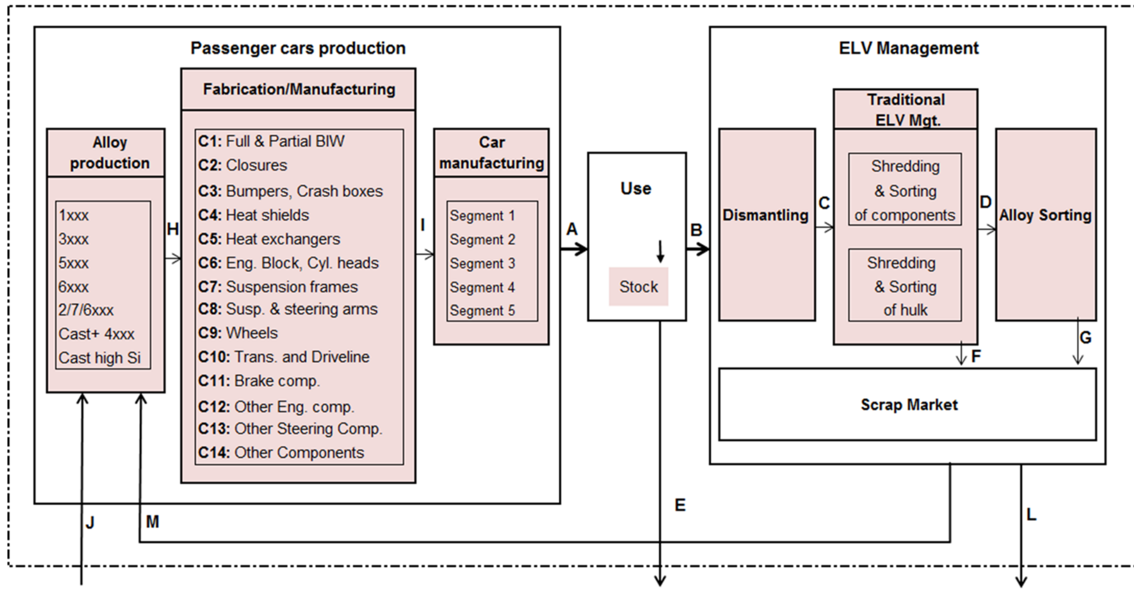

Fig. 2. System definition for the global automotive aluminum cycle.

recycling enter the ELV management process, in which some components are dismantled and kept separate from the shredding process, while the remaining components are usually shredded and sorted by air knife, magnetic sorting, sink float, or eddy current, which results in one mixed aluminum scrap fraction. Further alloy sorting may be introduced, for example, based on laser-induced breakdown spectroscopy (LIBS) or hand sorting. The overall loss of aluminum from shredding and sorting processes is shown as a flow leaving the system (L). Flow M is the ELV scrap that is recycled to produce alloys in combination with a flow J consisting of dross, turnings, new and old scrap from other applications, and primary aluminum and alloying elements.

Model Formulation

Determining the Vehicle Stock and Flow

At the core of the model is a global dynamic material flow analysis (MFA) model for the vehicle stock in use, which determines the number of cars that flow to the use phase (A) annually based on population, car ownership, and assumed vehicle lifetimes (normal distribution function). The principle of the model is described in a previous study,[6] and the Supplementary Information (SI) explains the specific aspects to this application.

Differentiating Vehicle Segments, Components, and Alloys

For a specific year t, the flow of aluminum in specific car segments and components in new vehicles ($N_{\mathrm{Al}}^{(\mathrm{S,C})}(t)$) is determined by the number of vehicles inflow in each segment ($\mathrm{N}^{(\mathrm{S})}(t)$), and the average aluminum mass of the component in that specific segment ($m_{\mathrm{Al}}^{(\mathrm{S,C})}(t)$). The aluminum flows that enter use in vehicle segment S and component C are determined by the following equation:

$$N_{\mathrm{Al}}^{(\mathrm{S,C})}(t) = N^{(\mathrm{S})}(t) * m_{\mathrm{Al}}^{(\mathrm{S,C})}(t) \quad (1)$$

For each of these 14 component groups, the content of various alloy classes (1xxx, 3xxx, 5xxx, 6xxx, 2xxx/7xxx/6xxx with Cu content >1%, 4xxx + low-impurity cast alloys, and cast high-Si alloys (high-impurity cast alloys) are defined, and based on the experts' opinion, it is assumed that the alloy content is constant for the entire period of time. The outflow from the use phase, with the same resolution of alloys, groups, and segments, is calculated based on a normal lifetime distribution function.

ELV Management

For each component group (C1–14) reaching the ELV management, three ELV indexes are defined. According to the experts' view on technical and economical viability of part dismantling, these three distinctions are as follows: (I) One fraction that is dismantled under the current practice, (II) another that has potential for dismantling, (III) and the remaining share that will be shredded under all circumstances. For the dismantling strategy, we assumed that the first two fractions of each component are dismantled.

Parameter Estimation

Detailed documentation on parameter estimation, such as population (Pop), vehicle ownership (Vp), and lifetime (L), is available in the Supplementary Information section. A summary of all the parameter estimation is shown in Fig. 3.

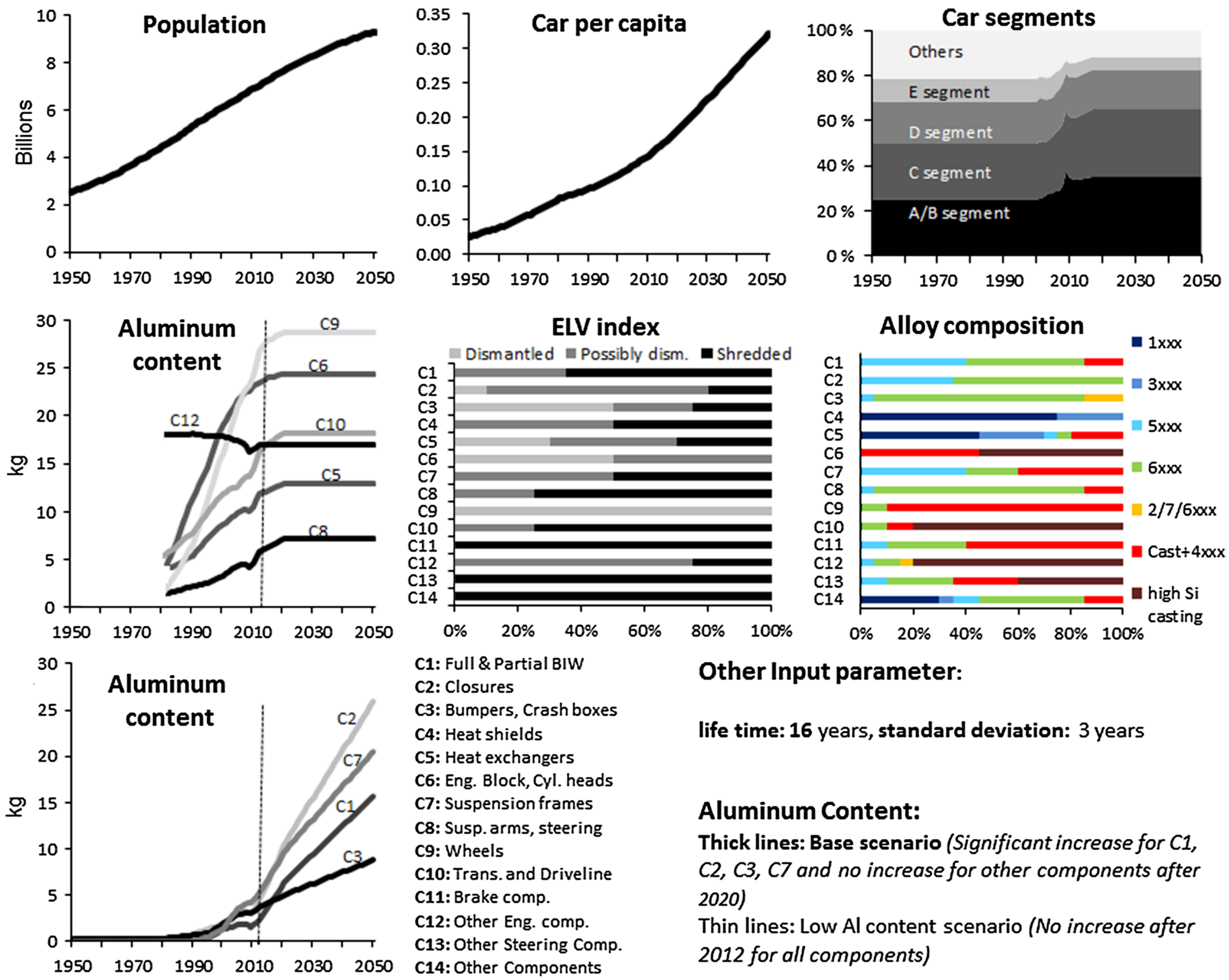

Fig. 3. Input parameters for the dynamic model.

Segments Splits ($N^{(S)}(t)$)

We learned from our previous study[6] that drive technology does not have a major effect because of a late penetration in the market. Therefore, the passenger car fleet is divided into five segments. S1 is A/B segment mini/small cars, S2 is C segment medium cars (small family cars), S3 is D segment large cars (large family cars), S4 is E segment executive cars (executive cars), and S5 includes the rest of the vehicle types (F segment luxury cars + S segment sport coupes). Market share data for different segments are available from 2000 to 2012, and a projection for 2017 on the global scale.[22] For the years prior to 2000, the segment share of the year 2000 is assumed, and the future segmentation share is assumed unchanged after 2017.

Aluminum Content for Vehicle Components ($m_{(\mathrm{Al})}^{(\mathrm{C})}(t)$)

The 14 components in this study are shown in Table I.

Data for the European aluminum content in 14 component groups and 5 segments between 1980 and 2020 are provided by the EAA and the Ducker studies.[23,24] The European aluminum amounts are used as the global assumption because European passenger car production corresponds to one-third of the global production.[15] Moreover, European cars use less aluminum than North American cars but more than Japanese and Asian cars.[16] Figure 3 shows the weighted average aluminum content in 14 components over time for the base scenario and a low-aluminum content scenario. Expert predictions and different studies have confirmed that aluminum growth will most likely be in BIW, closures, bumpers and crash boxes, and suspension frames.[16,17,23,24] The base scenario is based on experts' assumptions until 2020. After 2020, the aluminum content is assumed to remain constant except for component groups C1, C2, C3, and C7, which are assumed to increase. BIW (C1) and closures (C2) have the highest potential to grow, and it is suggested by experts to assume that the average aluminum content will be

Table I. Relevant component groups for aluminum used in passenger cars

Component	Manufactured Vehicle Part(s)
C1	Full body in white (BIW) and partial BIW
C2	Closures
C3	Bumpers and crash boxes
C4	Heat shields
C5	Heat exchangers
C6	Engine block and cylinder heads
C7	Suspension frames
C8	Suspension and steering arms
C9	Wheels
C10	Transmission and driveline
C11	Brake components
C12	All other engine components (pistons, housing for starter/dynamo, housing for water/oil, pump, oil pan, fuel injection system, cylinder head cover, support plates, *etc.*)
C13	All other steering components
C14	All other interior and exterior components

2.5 times greater in 2050 than in 2020. Subsequently, growth potential for bumpers and crash boxes (C3), and suspension frames (C7) are assumed two times greater in 2050 compared to 2020. In contrast to the base scenario, which is optimistic in aluminum use and governed by the ongoing light weighting trend, the low-aluminum scenario assumes that there will be no change in aluminum content after 2012.

Alloy Composition for Vehicle Groups

For the production of each of the 14 component groups, different alloy categories can be used (Fig. 3). It was suggested by experts to assume that the type of alloys used for a given component does not change over time because of lack of such detailed data. The following are the alloy categories: 1xxx, 3xxx, 5xxx, 6xxx, 2xxx/7xxx/6xxx with Cu $>1\%$, 4xxx + cast alloys (AlSi, AlMg) with low alloying/impurity content ($<0.5\%$ each), and cast alloys with high silicon content and higher alloying/impurity contents. Cast alloys with a low impurity content are primarily used in wheels, brake and steering components, structural body castings, and some of the engine parts and suspension frames, which in current practice are generally made from primary aluminum or wrought alloy fabrication scrap because of mandated properties and high cost for new alloy specifications and product design. Cast alloys with a high tolerance for impurities are primarily used in engine blocks and cylinder heads, transmissions and drivelines, and several steering subcomponents, and they have a high potential to accept scrap in their production.

Alloys Selection

The alloys selected from the typical alloys in automobiles for the source-sink diagram and are explained briefly in this section. More information is available in the Supplementary Information.

1070A This alloy has intermediate impurity levels between 1050 and 1100. The capacity to absorb scrap is close to zero for 1xxx series; however, they could be used as source material for any of the other alloys shown.

3103 The 3xxx-series alloys might be important from a recycling perspective because manganese, the main alloying element, is undesirable in many other alloys. Its main applications are fins and tubes in heat exchangers because of their high formability and corrosion resistance and medium strength.[18] Typical alloys are 3003 and 3103.[25]

5182 and 5754 Alloy 5754 is a typical choice when temperatures could exceed 80°C; in other cases, alloy 5182 may be used when increased strength is needed.[26–28]

6061 and 6082 Alloys 6061 and 6082 are typical selections when a higher strength is required, for example, in bumpers, suspension arms or wheels.[27–29] Alloy 6061 is more common in the United States, and alloy 6082 is more common in Europe.[5,28]

A356, 301, 319, and A380 The 3xx-series are the most widely used of all cast alloys. Silicon levels may reach up to 20%, and there is often a high concentration of other alloying elements.[20] Alloy A356 was chosen as an example of a primary cast alloy; it is widely used in wheels and other structural components, such as suspension frames or BIW.[5,28,30] Alloy A301 is used in pistons, contains approximately 1% Ni, and is included in the figure primarily to illustrate how the use of less common alloying elements can influence recycling. Alloys A319 and A380 are primarily used in cylinder heads and engine blocks[5,28] are the most important secondary alloys in terms of production volume,[31] and currently the main sinks for scrap.

ELV Index

ELV indexes are based on expert assumptions that consider economical feasibilities with currently available technology (Fig. 3).

ELV Collection Rate

In the United States, more than 95% of retired cars enter a comprehensive recycling system.[32] No definite global statistics are available regarding the number of ELVs that ends up in recycling plants, and therefore, the U.S. collection rate is used in the model.

ELV Management Efficiency

In ELV management, several losses may occur. There is aluminum loss during the shredding process to other systems, where several undesirable metals that cause contamination in the recycling system, such as Fe, Cu, Mg, and Zn, can enter the stream. In the system definition, there is a flow leaving ELV management, which represents the overall scrap loss during the ELV processes (L). In this study, the shredder yield is assumed to be 90%.[33] Scrap remelting losses are also considered in the ELV management process and are assumed to be 8%.[33] The resulting overall yield from ELV management is 83%. Flow M leaves the ELV management system to be recycled into new alloys for use in passenger cars.

RESULTS AND DISCUSSION

Figure 4 illustrates the aggregate simulation results for the alloy groups entering use in the form of vehicles (flow A) and the alloy groups recovered from ELV management in the form of scrap (flow M). Three alloy classes dominate automotive aluminum use, which is reflected in both new vehicles and scrap: cast alloys with high impurity tolerance ("cast high Si"), cast alloys with low impurity content ("4xxx + cast alloys"), and 6xxx alloys. For the base scenario, the demand for 6xxx alloys is expected to grow by a factor of three between 2010 and 2030, from 2.3 to 6.5 million metric tons (MMT), and the total demand for cast alloys is estimated to increase in the same period by a factor of two, from 5.4 to 11.5 MMT. Figure 4 also confirms many other previous studies that the total scrap supply is expected to surpass the demand for high-impurity cast alloys in the next few years. Because the cast high-Si alloys currently are the only relevant sink alloy class, this graph highlights the importance and urgency of identifying alternative sink alloys for automotive aluminum scrap that can act as intermediate reservoirs. In addition, the figure shows the need for effective strategies by which to separate alloys sufficiently to reach the required qualities of these sink alloys. Figure 5 illustrates flows of components (area of circles) and their alloy composition (colors) in new vehicles entering use (flow A) and in scrap recovered from ELV management (flow M) in 2030. Flow M is determined for component dismantling before shredding and alloy sorting to assess the effectiveness of dismantling and alloy sorting in the changing context. The overall scrap supply is expected to grow to 9.3 MMT in 2030. In addition, the share of wrought alloys in ELV scrap increases from 35% in 2010 to 43% in 2030. This mixed scrap from shredders can be used only for cast high-Si content alloy demand, which is expected to grow to 5.1 MMT in 2030, and it is significantly less than the expected ELV scrap in 2030. Therefore, without sorting or dismantling and under the assumption that no dilution is required for the production of cast, high-Si content alloys, there

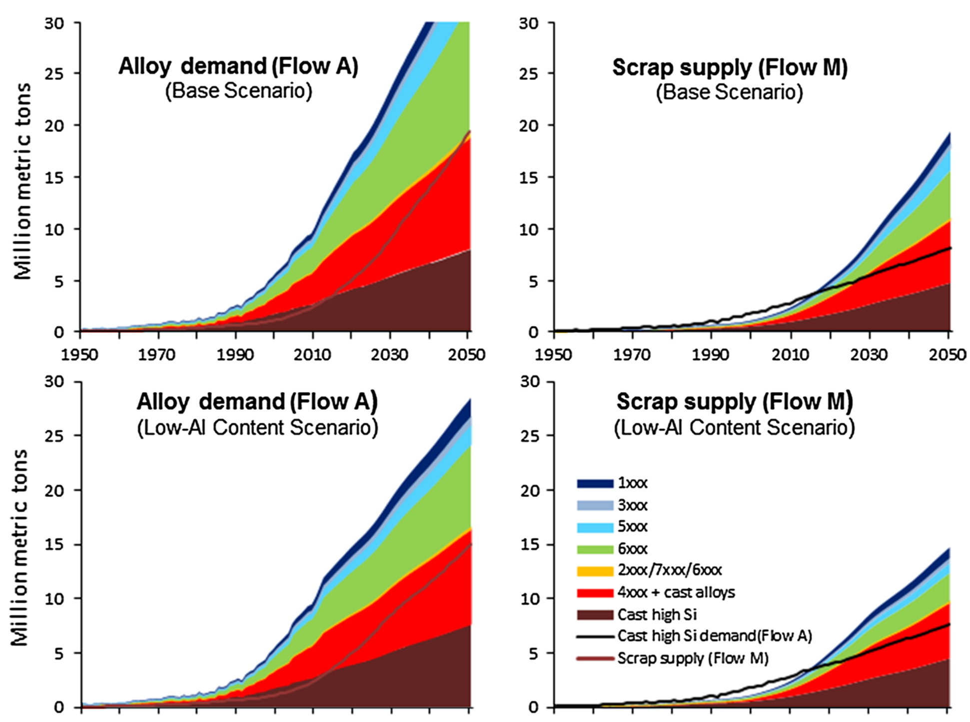

Fig. 4. Global passenger cars alloy demand and scrap supply for the base scenario and the low-Al content scenario. The graphs on the left show the alloys demand (flow A) and the total scrap supply (brown lines). The graphs on the right show the scrap supply (flow M) of different alloys and cast high-Si alloy demand (black lines).

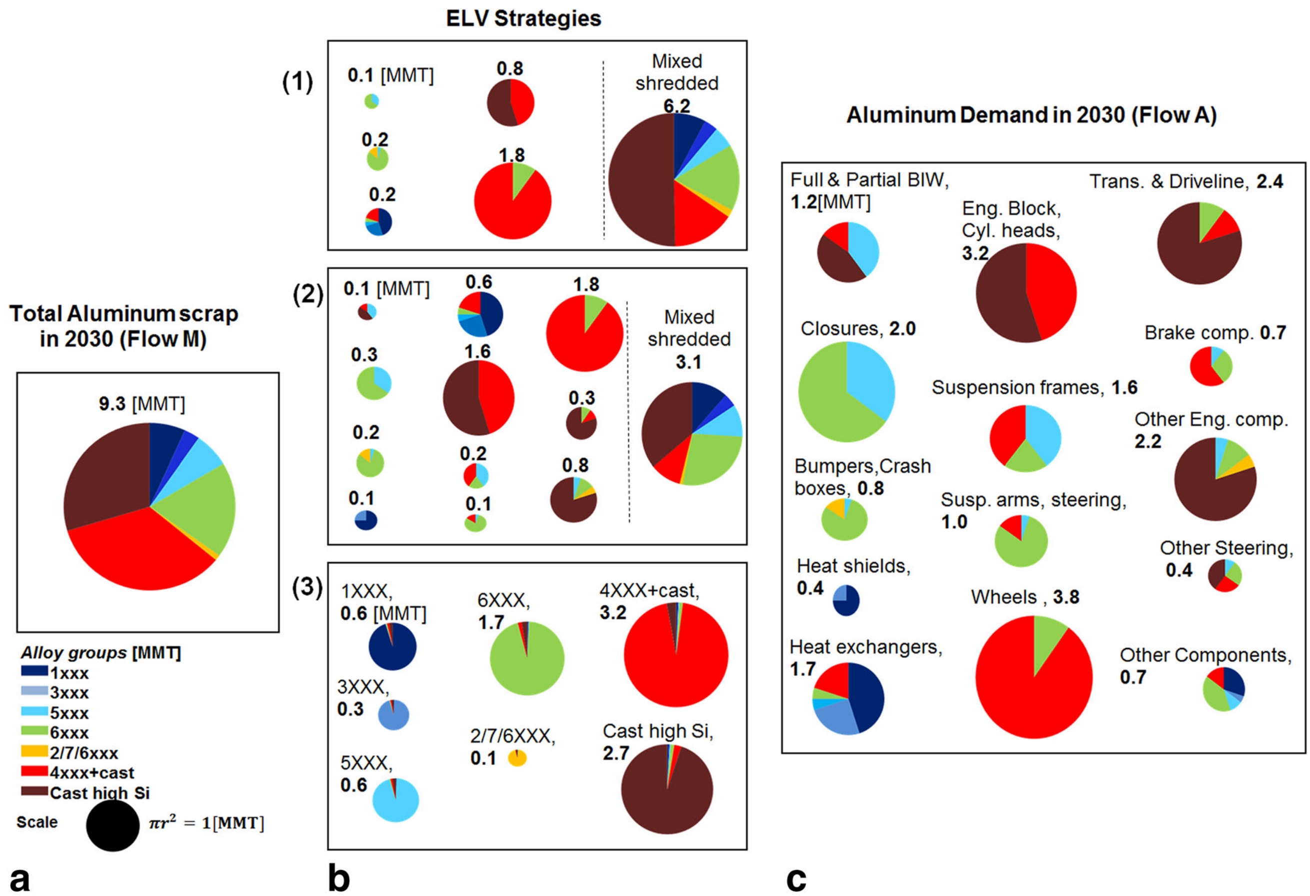

Fig. 5. The figure shows a snapshot for the year 2030: (a) total aluminum scraps (flow M); (b) ELV strategies considering (1) current dismantling strategy, (2) intensive dismantling strategy, and (3) alloy sorting; and (c) aluminum demand for car components (flow A).

will be a scrap surplus of approximately 4.2 MMT in 2030.

An ambitious dismantling strategy prior to shredding would reduce the shredded scrap bulk by approximately 67% in 2030 (from 9.3 to 3.1 MMT). Even with the high dismantling option, in the absence of component-to-component recycling, available scrap that can only be used to produce cast high-Si alloys would increase the demand and create a surplus in 2030 (including the cast high Si alloys in dismantled components). By introducing alloy sorting after shredding, there would be a greater possibility to use scrap in intermediate reservoirs, although the scrap streams would still be mixtures of different alloys within each series. The proposed alloy sorting requires high-tech facilities such as LIBS to minimize the impurities. A cost-benefit analysis is needed because the facilities are expensive.

To recover and recycle all the aluminum from ELVs within the automotive sector, an analysis of the alloy flows on a component-by-component level is required (Fig. 6). Cast alloys with a high impurity tolerance, the most attractive sink alloys, are primarily used in engine blocks and cylinder heads, other engine parts, transmissions, and drivelines. All of these components are suitable candidates for component-to-component recycling, but their future as an important sink alloy is in danger due to the downsizing of internal combustion engines and the introduction of alternative powertrains. In contrast, aluminum wheels have the largest, yet unused potential for component-to-component recycling. They are the largest component group, they are easy to dismantle, and they use homogenous alloys. Nonetheless, obsolete wheels are currently used mainly as a source of scrap for cast high-Si components. Wheel-to-wheel recycling is impeded by the fact that automobile producers' practice requires safety-relevant components to be made from primary material only. Changing the specifications for wheels to allow for component-to-component recycling would be expensive for the automobile manufacturers because it would require the development of improved casting processes, investments in new equipment, and costly technical tests, where the urgency for such a change would likely come from the aluminum recycling industry. Using wheels scrap to produce suspension arms is technically possible,[19] even though the demand for suspension arms is not high enough to absorb a large amount of wheels scrap. Bumpers and crash boxes have changed their

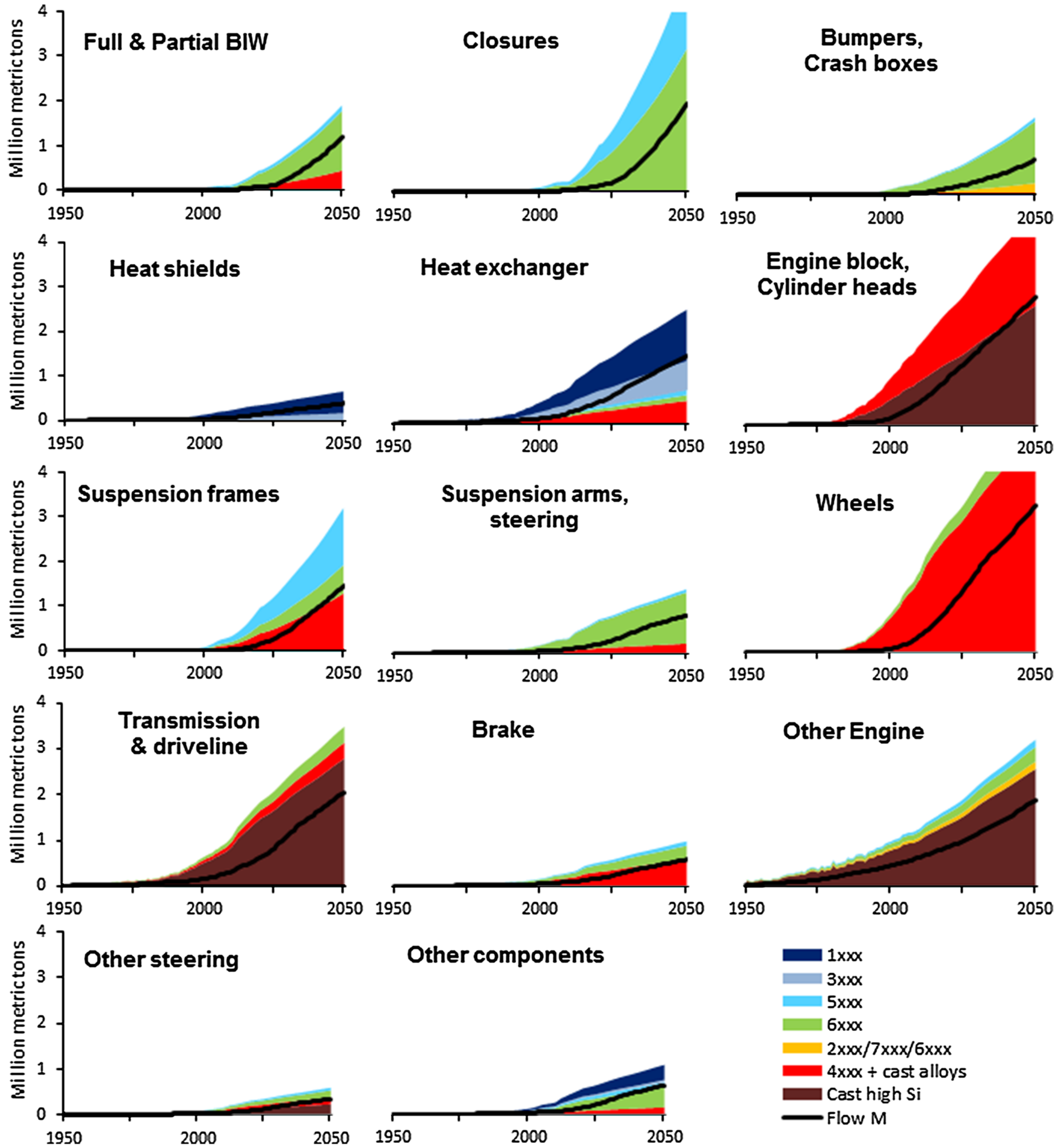

Fig. 6. Global alloy demand for 14 major car components versus the overall scrap (flow M) for the base scenario from components.

composition. Although they used to be made of zinc-containing 7xxx alloys, they consist today mainly of 6xxx alloys. Although bumper-to-bumper recycling is technically possible with some of the existing practices in recycling plants,[19] it is practically limited to bumpers made of 6xxx alloys because bumpers made from 7xxx are no longer produced and 6xxx alloys are very ineffective in absorbing 7xxx alloys because of their high zinc content. Such shifts in alloy use toward higher purity within a component group can pose severe limits to recycling. The model used here cannot treat such changes in component composition and may thus produce too optimistic results; however, these changes resulting from the component composition are deemed less important than the changes from increased penetration of aluminum components in general and should not affect the main conclusions.

CONCLUSION

Drastic changes in ELV management practices are necessary to make use of the growing potential for recycling and to avoid an unusable surplus of aluminum scrap. The main solution options recognized in this study are as follows:

1. Further dismantling and efficient component-to-component recycling may require new standards for the production of safety-related components made from scrap. Enhanced dismantling as long

as the dismantled parts are keeping separate from the mixed shredded scrap could be a very effective strategy. Wheels, closures, suspension frames, heat exchangers, bumpers, and crash boxes are recognized as the best candidates for component-to-component recycling. Wheels are a key scrap flow that needs to be redirected and can make a very large contribution to mitigating scrap surplus if recycled into an intermediate reservoir.
2. Alloy sorting of mixed shredded scrap for components that are too expensive to dismantle. Additional alloy sorting requires further advanced technology development (such as LIBS) and high penetration of such technologies in the market to avoid impurities in the scrap stream.
3. New recycling-friendly alloys are being developed for both wrought and cast applications, which are functioning as "intermediate reservoirs." Although intermediate reservoirs may not be the final solution to the alloy problem, they could be important in a transition phase by delaying the problem while more advanced separation techniques are developed.

It is important to look for alternative sink alloys. The most versatile sinks are cast alloys, such as 301, 319 and A380; however, these alloys have high alloying element content, making them the least flexible source alloys because they can only be recycled into similar alloys. Other than these cast alloys, there are few other alloys that can absorb mixed scrap. One option could be to use alloy 6082 as a sink for a mixture of wrought alloys.

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ELECTRONIC SUPPLEMENTARY MATERIAL

The online version of this article (doi:10.1007/s11837-014-0900-8) contains supplementary material, which is available to authorized users.

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