IO-MFA-based linear programming for the quality-oriented End-of-Life vehicle scrap recycling

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**Abstract**

Recycling is one of the key to develop sustainable society. However, as functions of products become higher and more complex, the recycling also become more complicate and harder recently. Since metals can be infinitely recycled in principle, sometimes they are thought as the easily recyclable material by remelting. However, according to the thermodynamics, they contaminate each other and their separation become difficult once they are remelted together. Thus, separation and sorting of metals before remelting is the important treatment in the end of life (EoL) products recycling. Furthermore, because metal materials are not pure metals but alloy in many cases, not only exogenous but also endogenous contamination by other metals must be considered in the metal recycling. Therefore, both separation of sorting of metal materials in EoL products and efficient utilization strategy recusing contaminations and losses of metals are required for the development of the sustainable metal use society.

In this study, by combining linear programming (LP) and waste input-output material flow analysis (WIO-MFA), the strategy of efficient utilization of steel alloying elements (AEs) contained in EoL vehicle (ELV) derived steel scrap is optimized as a case study.

**Introduction**

The efficient management of resources is indispensable in the development of a sustainable society. In particular, metals are essential resources in modern society, the efficient use of them is a key to develop sustainably.[1-3](#_ENREF_1) In this circumstance, Reck et al.[3](#_ENREF_3) noted that the recycling of metals from end-of- life (EoL) products has become much more complicated and challenging due to complex structure and composition of recent functional products. Because metals are not basically used independently but combined and/or alloyed, careless melting in recycling may cause unintentional alloying and dissipation according to thermodynamic distribution tendencies during melting.[4](#_ENREF_4) Therefore, we must consider appropriate recycling methods to efficiently recover as much metals as possible from EoL products.

For the efficient metal recycling, sorting of metal scrap is one of the key concepts.[3](#_ENREF_3),[5](#_ENREF_5),[6](#_ENREF_6) In our previous studies,[5](#_ENREF_5),[6](#_ENREF_6) steel alloying elements (AEs) contained in automobiles were quantified and the importance of the scrap sorting before melting in recycling phase considering AEs contents was pointed out. Scrap allocation considering scrap quality was argued in several previous researches about aluminum scrap recycling since the reduction of impurity accumulation into recycled aluminum is important subject.[1](#_ENREF_1),[7-9](#_ENREF_7) Gaustad et al.[1](#_ENREF_1) defined the types of allocation method as pseudoclosed loop scrap allocation and market-based scrap allocation. In the pseudoclosed loop scrap allocation, scrap derived by certain EoL product is allocated to produce the same product. However, Gaustad et al. correctly pointed out that all scrap is purchased and allocated by secondary producers first to produce secondary material, thus, the material producers have an important role in determining the actual composition of aluminum material flows. Because base metals such as aluminum and steel are utilized widely in various industries, market-based scrap allocation is feasible to simulate actual appropriate scrap recycling. In contrast to aluminum scrap recycling, quality oriented recycling and research for steel have rarely subjected except the contamination of copper[10](#_ENREF_10),[11](#_ENREF_11) because the production of AEs containing special steel have been relatively smaller than mass produced ordinary carbon steel, and AEs contents in steel scrap could be diluted by ordinary steel scrap enough or oxidized into slag. However, considering recent increase of automobile production and its use of special steel, quality control of steel scrap will be important subject for the future as well as aluminum.

In this study, the AEs losses minimizing effect of appropriate treatment and recycling of ELVs-derived steel scrap is evaluated by linear programming (LP) combining with the waste input-output material-flow analysis (WIO-MFA)[12](#_ENREF_12),[13](#_ENREF_13) as a case study. By means of LP, the appropriate matching of sorted ELV-derived scrap and secondary steel materials aimed at efficient utilization of AEs contained in the scrap was optimized. Applying IO data to LP as constraints, market-based allocation can be achieved naturally according to the supply chain indicated in IO table. For this feature, the effects of the scrap allocation for whole economy can be obtained whereas previous aluminum studies only took account of the aluminum production and/or recycling.[1](#_ENREF_1),[7-9](#_ENREF_7) Furthermore, since WIO-MFA table developed in our previous research[5](#_ENREF_5),[6](#_ENREF_6) was compiled AEs demands in productions of various grades of crude steel, upper and lower limits of AEs concentration in recycled material are not necessary to set exogenously. As Løvik et al. pointed out that because there are quite a few industrial standards for alloys, the definition of the limits of AEs concentration is one of the difficulty of the allocation model approach.[9](#_ENREF_9) In the present study, this kind of difficulty has been cleared in the phase of making WIO-MFA table in our previous study.[5](#_ENREF_5),[6](#_ENREF_6)

**Methods and Data**

**IO-based LP model**

The integration of IO and LP have been researched for more than half a century.[14](#_ENREF_14),[15](#_ENREF_15) In the integration, the optimization of technical choice for the achievement of objective functions is a main subject. In the general IOA, $n$ kinds of goods are produced by $n$ kinds of each single technology to produce corresponding goods. Thus, the number of goods and technologies for producing goods are the same. In the IO table extended for LP, in contrast, there are more than one technologies for the production of homogeneous good. In other words, $n$ kinds of goods are produced by $m$ kinds of technologies ($n<m)$. Therefore, although the matrix of input coefficients $A$ in standard IOA is square ($n×n)$, the input coefficient matrix for IO-based LP become non-square$(n×m)$. According to the conversion, identity matrix $I$ in the basic formula $\left(I-A\right)x=f$ is replaced by technical choice considered identity matrix $H$ that is an $n×m$ matrix of zeros and unities, and its $(i,j)$-component $h\_{ij}$ is defined by

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| $$h\_{ij}=\left\{\begin{array}{c}1\\0\end{array}\right. \begin{matrix}technology j produces goods i\\otherwise\end{matrix}$$ | (2) |

By the application of non-square matrices $H$ and $A$, technology mixes for the production of homogeneous goods can be optimized to meet an objective function by LP. Using these matrices, IO-based LP is conducted to optimize following problem.

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| $$minimize cx,$$ | (3) |
| $$subject to \left(H-A\right)x=f$$ | (4) |
| $$x\geq 0,$$ | (5) |

where $c$ is an $n×1$ vector consisted of unities and zeros to distinguish minimization objective from other outputs, $f$ is an $n×1$ vector represents final demands for goods. For more detailed explanation, see Kondo et al[16](#_ENREF_16).

Kondo et al. developed the WIO-LP[16](#_ENREF_16) which optimize the selection of waste treatment and recycling technology under the objective of environmental loads minimization based on WIO.[17](#_ENREF_17) Lin applied this WIO-LP for waste water treatment.[18](#_ENREF_18) By applying this study to the present study, the optimization method for matching between ELV-derived scrap supplies and demand for the EAF steel making is developed.

**Data setting for the development of the WIO-MFA table for LP**

Here, sorted ELV-derived scrap utilization in the EAF steelmaking process is simulated. In other words, technology mixes of conventional and sorted ELV-derived scrap using EAF steelmaking are optimized by LP. As a case study of the application of this model, ELV-derived scrap recycling in Japan in 2005 was simulated because of adjustment for IO-data and higher data availability. In 2005, 30,518 kt of iron and steel scrap including 2,348 kt of ELV-derived scrap was used as an iron source.[19](#_ENREF_19) As an assumption, 2,348 kt of ELV-derived scrap can be totally sorted by parts and separately used besides other iron and steel scrap in this study. Here, ELV-derived scrap consists of 8 kinds of parts: body parts, suspension parts, shafts, steering parts, interior parts, transmission parts, breaks and exhaust parts. The sorted ELV-derived scrap is utilized for EAF steelmaking under the following regulation considering its AEs contents.

1. The total demand of an AE $e$ for the production of EAF crude special steel $j$ is substituted by contents of $e$ in sorted scrap $i$.
2. If the amount of more than one kind of accompanying other AE $e'$ and iron with scrap $i$ exceed the demands of them, scrap $i$ cannot be used to substitute all of the demand of $e$ in special steel $j$.
3. Besides scrap $i$, each $e'$ are supplied to satisfy the demands of them by addition of virgin sources such as ferroalloys and/or metals. Also in case iron supply exceed the demand due to the ferroalloys derived iron, scrap $i $cannot be used for the substitution.
4. For ordinary steels, ELV-derived scrap can be used unless the total of concentrations of chromium and nickel derived by ELV-derived scrap is higher than 0.35%.[20](#_ENREF_20)
5. Rest of iron demand is filled by addition of non-ELV-derived steel scrap.

Considering the process flow of EAF steelmaking, that insert scrap first and oxidize/remove impurities before the input of virgin sources of AEs, the yield losses of AEs in the scrap are set higher than virgin sources. Applying this regulation, 108 kinds of ELV-derived scrap using EAF steelmaking for 17 kinds of crude steels are defined. Details are indicated in SI.

From this data setting, required amounts of each sorted scrap, virgin sources of AEs and non-ELV-derived steel scrap for the ELV-derived scrap using EAF steelmaking are obtained, and these input coefficients can be calculated. In this calculation, other inputs except scrap and AEs sources are the same as conventional EAF steelmaking. Consequently, 518$×$625 of input coefficient matrix was obtained for LP calculation.

As the objective functions for the optimization by using LP, the minimization of consumptions of AEs virgin sources are applied. Here, eight kinds of virgin sources of AEs are the targets; ferromanganese, silicomanganese, metallic manganese, ferrochromium, ferronickel, metallic nickel, ferromolybdenum, and molybdenum oxide briquettes. Objective functions are defined in two types. The first is the minimization of total consumption of eight kinds of virgin sources, and the others are the minimization of consumptions of virgin sources by each AE. Thus, definitely, five objective function are defined; minimization of total, manganese sources, chromium sources, nickel sources and molybdenum sources consumptions.

Besides constraints based on $\left(H-A\right)x=f$ , usable ELV-derived scrap amount is defined as constraint that all amounts of each kind of scrap are used for the production of EAF crude steels. That means the total amount of scrap supply is fixed as 30,518 kt that is the total amount of iron and steel scrap recycled by EAF in Japan in 2005.

**Results and Discussion**

**Scrap sorting to prevent the loss and dilution of AEs**

In this case study, 2,348 kt of ELV-derived scrap was recycled as an iron source in EAF-based steelmaking.[19](#_ENREF_19) Estimating amounts of each sorted ELV-derived scrap based on the previous report, total weight of ELVs was calculated as 4,050 kt and the breakdown was indicated in Table 1. Since about 4 million units of ELVs were discarded every year in Japan,[21](#_ENREF_21) this assumption would not be far from reality. The contents of AEs were also shown in Table 1 and the total amounts of AEs associating with 2,348 kt of recycled ELV-derived scrap corresponded to about 9.3% of annual consumption of AEs derived by virgin sources at the EAF steelmaking process.[22](#_ENREF_22) Although the ELV-derived scrap contains considerable contents of AEs, about 93% of the ELV-derived scrap are recycled to ordinary steels that are not so much require contents of AEs by the EAF steelmaking process[6](#_ENREF_6). Therefore the present recycling of the ELV-derived scrap is inefficient from the view point of the recycling of AEs.

Focusing on the efficient recycling of AEs in the ELV-derived scrap, the matching of each part scrap and secondary steels were optimized by means of IO-based LP. Figure 1 (upper half) shows optimized matching of separated ELV-derived scrap with steel materials to efficiently recycle AEs in the ELV-derived scrap under the objective function aimed at minimizing total consumption of virgin sources of AEs. Relatively low AEs concentration of parts scrap such as body, steering, and breaks were mainly matched with ordinary steel. In contrast, parts scrap which have over 0.5% of AE concentration such as suspension, shaft, and exhaust tend to be used to produce alloy steels in the optimal matching.

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| Table 1 Amounts of scrap by parts and its contents of alloying elements |
|  | Scrap (kt) |  | Alloying elements (t) |
|  | Weight  |  | Mn | Cr | Ni | Mo |
| Body | 1,299 |  | 5,869 | 2,365 | 979 | 135 |
| Suspension | 175 |  | 1,244 | 384 | 96 | 24 |
| Shaft | 166 |  | 689 | 1,168 | 312 | 62 |
| Steering | 127 |  | 442 | 414 | 155 | 21 |
| Interior | 239 |  | 418 | 121 | 47 | 3 |
| Transmission | 139 |  | 301 | 422 | 161 | 20 |
| Breaks | 66 |  | 116 | 47 | 16 | 2 |
| Exhaust | 137 |  | 585 | 12,889 | 3,063 | 260 |
| Iron source total | 2,348 |  | 9,664 | 17,811 | 4,828 | 527 |
| Removed | 1,702 |  | 5,801 | 9,291 | 1,320 | 290 |
| Total | 4,050 |  | 15,465 | 27,102 | 6,148 | 817 |

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| Figure 1 Optimized matching with secondary steel (Top), and flow of alloying elements accompanying with sorted ELV-derived scrap (bottom) |

AEs accompany the optimal scrap usage like Figure 1 (bottom half). In the ELV treatment process, unignorable amounts of AEs are removed accompanying with engines. Since about 40% of removed engines were returned to the steel recycling process[23](#_ENREF_23), AEs in the returned engine-derived steel scrap should be also efficiently recycled in the EAF steelmaking process. After the ELV treatment process, 62% of manganese, 66% of chromium, 79% of nickel, and 65% of molybdenum in the ELV-derived scrap respectively move to recycling process accompanying with each part. Flows of AEs on the matching consist mainly of two large flows accompanying with body and exhaust parts. Although the concentrations of AEs in body scrap are not so high, large portion of AEs especially manganese accompany with body scrap because of the largest weight of body scrap. The body scrap was matched with ordinary steel and other special steel, and used as iron source rather than the source of AEs. On the other hand, exhaust parts strongly dominate the flows of chromium (48%), nickel (50%) and molybdenum (32%) in spite of its relatively smaller weight. That means the appropriate treatment for exhaust parts is important for the efficient use of AEs in ELV-derived scrap. The exhaust parts scrap is mainly matched with stainless steels. By using this scrap to produce stainless steels consuming large amounts of chromium and nickel, the AEs in this scrap can be efficiently utilized as a source of them. In addition to these large flows, suspension and shaft parts which have relatively high concentration of AEs deliver AEs to alloy structural steel and bearing steel respectively.

**Efficiency of the sorting**

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| Table 2 Reduced consumption of alloying elements derived by virgin sources and utilization ratio of alloying elements in ELV-derived steel scrap |
|  | Mn | Cr | Ni | Mo | Total |
|  | t | % | t | % | t | % | t | % | t | % |
| Total accompanying | 9,664 | - | 17,811 | - | 4,828 | - | 527 | - | 32,829 | - |
| Mixed(current case) | 689 | 7.1 | 1,249 | 7.0 | 343 | 7.1 | 37 | 7.0 | 2,318 | 7.1 |
| All sorted | 7,337 | 75.9 | 16,690 | 93.7 | 4,429 | 91.7 | 464 | 88.1 | 28,920 | 88.1 |
| Simple model | 7,015 | 72.6 | 16,646 | 93.5 | 4,404 | 91.2 | 462 | 87.7 | 28,528 | 86.9 |

Table 2 shows reduced amounts of virgin source derived AEs consumptions and utilization ratios of AEs in ELV-derived scrap. By disassembling and sorting ELV scrap, totally 88% of AEs in ELV-derived scrap, that correspond to about 8.2% of annual consumption in EAF steelmaking, can be utilized for the secondly steelmaking. In comparison with current ELV recycling, this utilization ratio is quite high because the use of mixed ELV-derived scrap in special steelmaking by EAF is only 7% and almost AEs flow into ordinary steelmaking.[6](#_ENREF_6) Consequently, needless to say, up to 7% of AEs in mixed ELV-derived scrap can be utilized as a source of AEs. Therefore the scrap sorting has a large advantage over the conventional ELV recycling for the efficient utilization of AEs in the ELV-derived scrap.

However, to achieve such high utilization ratio of AEs, ELV recycler must disassemble and sort ELV scrap substantially by taking additional costs and operation time. Considering the feasibility of disassembling and sorting, the simple scenario of sorting was developed instead of all parts sorting. In this scenario, only 4 kinds of relatively high AEs containing parts are separately sorted; suspension, shafts, transmission and exhaust parts, and suspension parts are assumed to be sorted with breaks because of their near position in automobiles. Except these separated parts, the rest of parts and body are treated together. This treatment process would not difficult for the ordinary ELV recycler.[23](#_ENREF_23),[24](#_ENREF_24) As the result of matching optimization, although the reduction of consumption and utilization ratio of AEs were slightly lower than the all parts sorting scenario, this simple scenario can also achieve enough efficient recycling ratio (87%) of AEs in the ELV-derived scrap.

**Conclusion**

In the case study of ELV-derived recycling, significant reduction of AEs losses could be avoided by conducting optimal treatment and recycling. By applying IO data for the LP constraints, EoL products recycling can be considered within the economic system described in IO table. That means the repercussion effects and impacts of the recycling can be easily obtained by this method. In the present case study, only AEs utilized amount was an objective of maximization. However, in the practical cases of recycling, cost and/or environmental burden minimization would be the objective. Since the IO analysis has high extensibility, these parameter can be included in this model as a next development of this model.

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