# Pitfalls in Recycling of Ferrous Metals

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# *Recycling is a major component in closing the cycle between industrial products and the environment*

- End-of-Life legislation is designed to accomplish this purpose and set targets for the recycling rate of discarded products.
- The EU legislation, for example, requires 85% of cars to be recycled (Directive, 2000/53/EC of the European Parliament and the council of 18 September 2000 on end of life vehicles.).

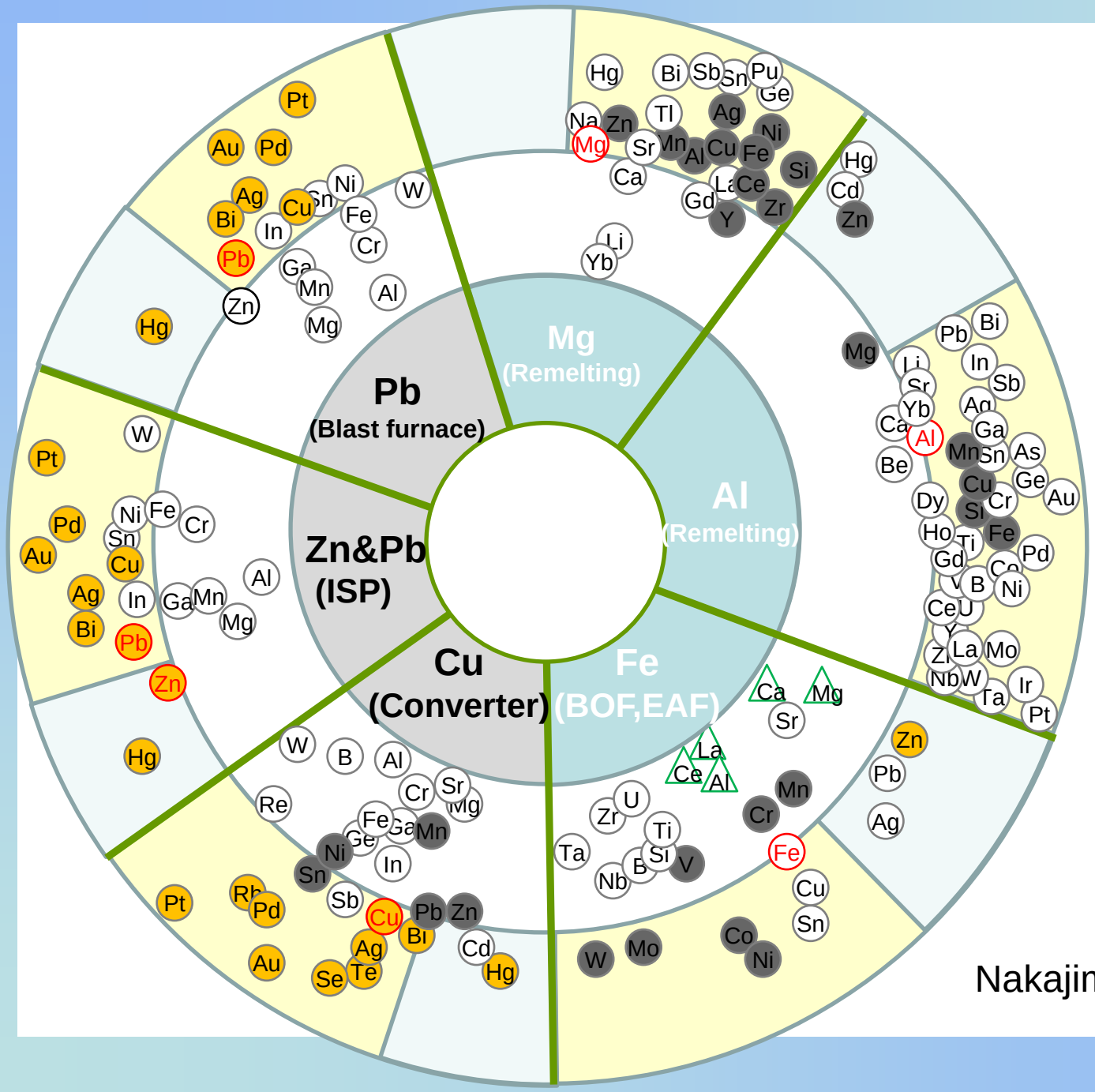
Amini et al. J. of Cleaner Production 15, 907-913 (2007)

# However…

- Recycling can create streams with a lower quality which are un-economical to recycle partially due to the limitations of thermodynamics, which makes refining difficult.

  Amini et al. J. of Cleaner Production 15, 907-913 (2007)

- Mixing (incomplete separation) of metal species in the EoL phase that cannot be properly accommodated by current metallurgical processes that are optimized for processing natural ores




to Metal phase

Elements that have distributed among the metal phase as a solid or liquid metal

to Slag phase

Elements that have distributed among the slag phase as oxide

to Gas phase

Elements that have evaporated and distributed among the gas phase.

Recoverable element (as pure metal)

Alloying element

Deoxidation agents

Nakajima et al. ES&T (2011)

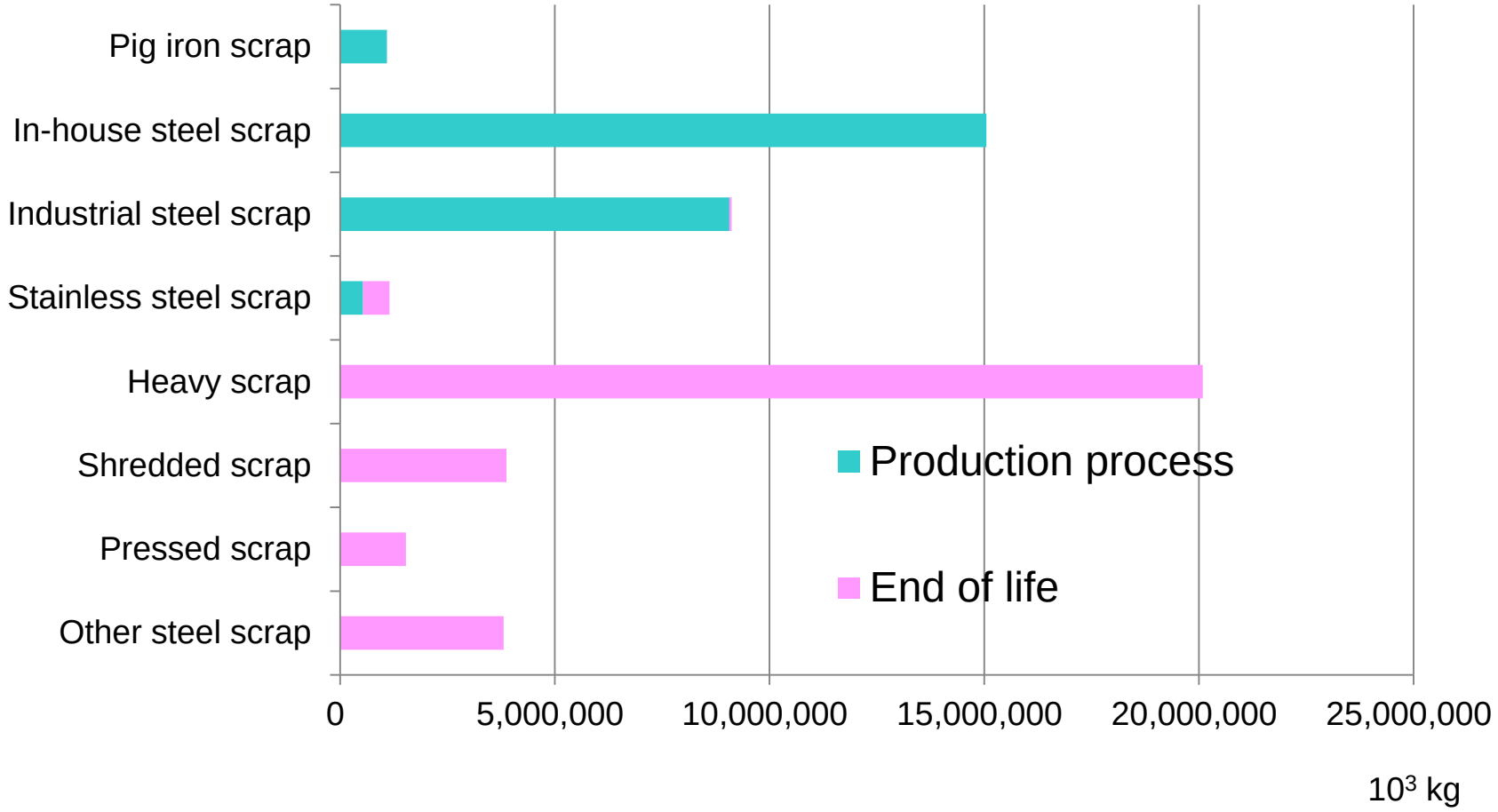
# Quality losses of metals in recycling: literature review

- Recycling of End of Life Vehicles (ELV):
  - Castro, Remmerswaal, Brezel, Reuter: Res. Cons. Rec. 52, 2007
  - Amini, Remmerswaal, Castro, Reuter: JOCP. 15, 2007
- Cu in Iron & Steel (I&S) scrap
  - Igarashi, Daigo, Matsuno, Adachi: ISIJ Int. 47, 2007
- Losses of alloying elements in recycling (refining processes):
  - Nakajima, Yokoyama, Matsuno, Nagasaka, ISIJ Int. 47, 2007
  - Nakajima, Takeda, Miki, Matsubae, Nakamura, Nagasaka, ES&T 44, 2011
  - Hiraki, Takeda, Nakajima, Matsubae, Nakamura, Nagasaka, Science & . Tech. Adv. Materials. 12, 2011

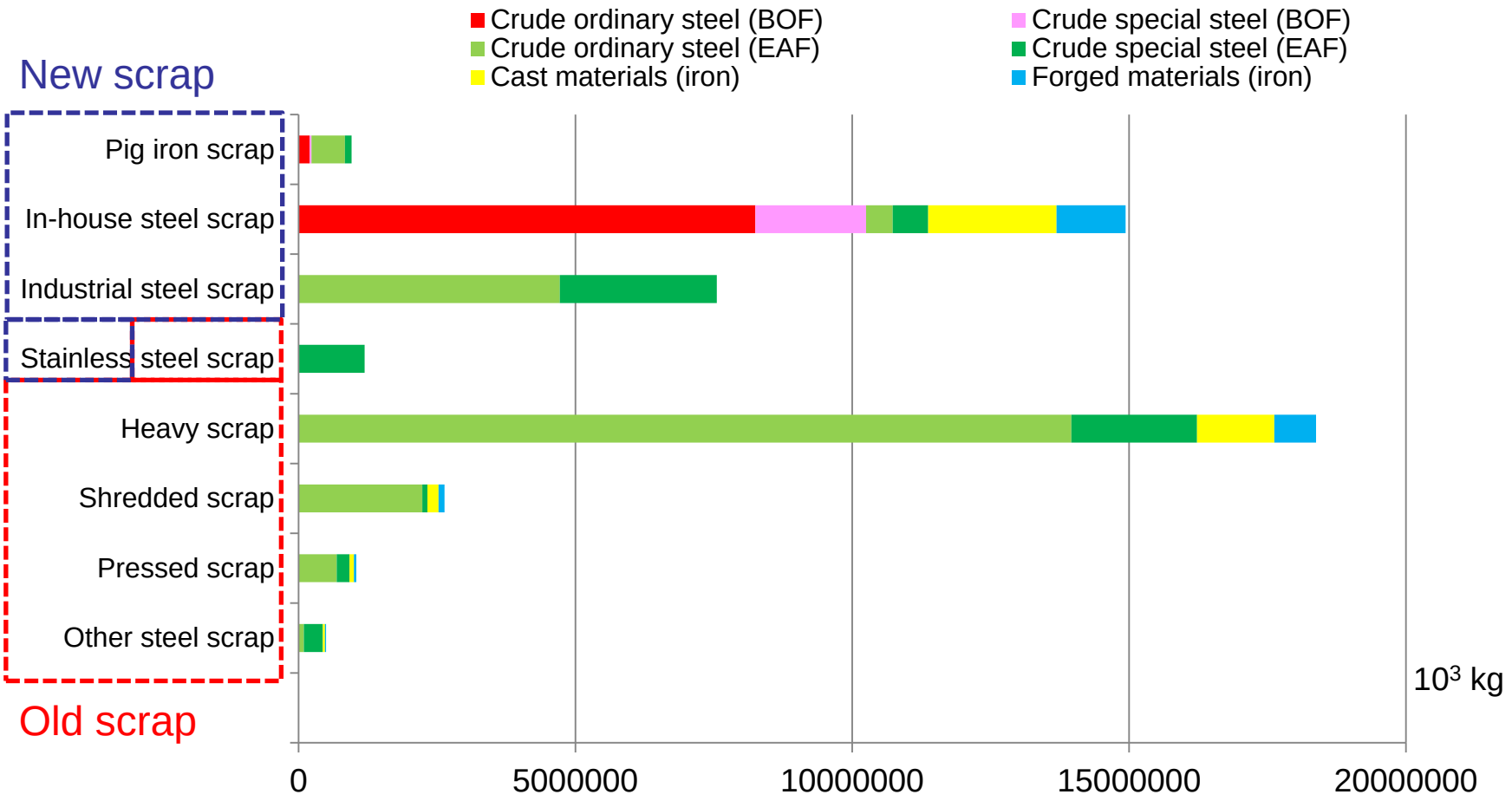
# Purpose

- Quality issues of I&S scrap from ELVs
- Quantifying the losses: Castro et al/Amini et al 2007
  - Material losses
  - Quality losses
  - Dilution losses
- Hybrid approach at high level of resolution
  - Nakamura/Yamasue: ES&T 44, 2010: dilution of scrap in EAF
  - Nakamura/Nakajima: Mater. Trans 46, 2005: WIO-MFA
  - Eight I&S *scrap categories* distinguished by origins: Matsubae et. al ISIJ Int. 51, 2011
  - Separation/liberation of 25 parts/components from ELV: Tasaki 2003

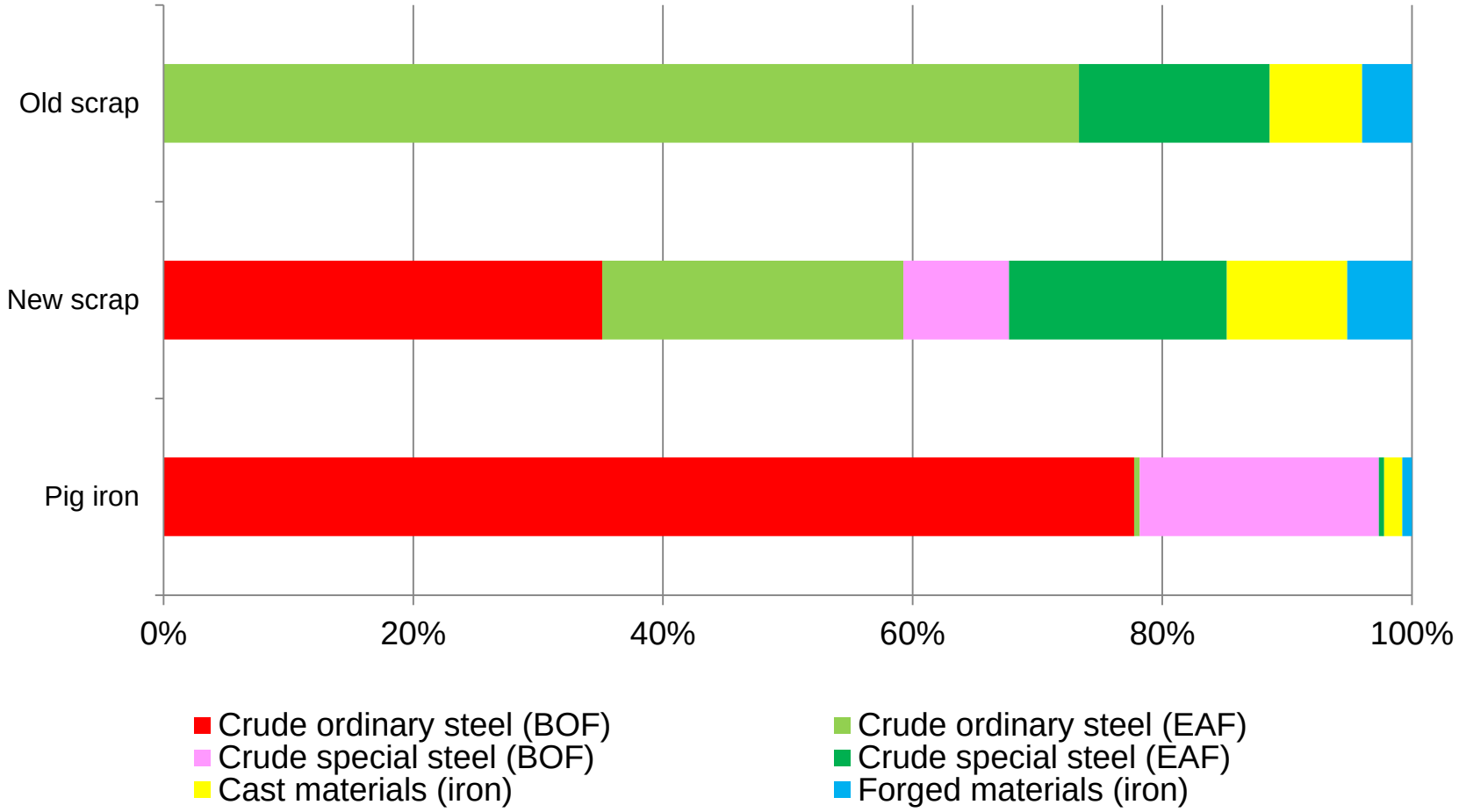
# Origin of I&S scrap 2005:
## Matsubae et. al. ISIJ Int. 51, 2011



# Use of I&S scrap in steel production



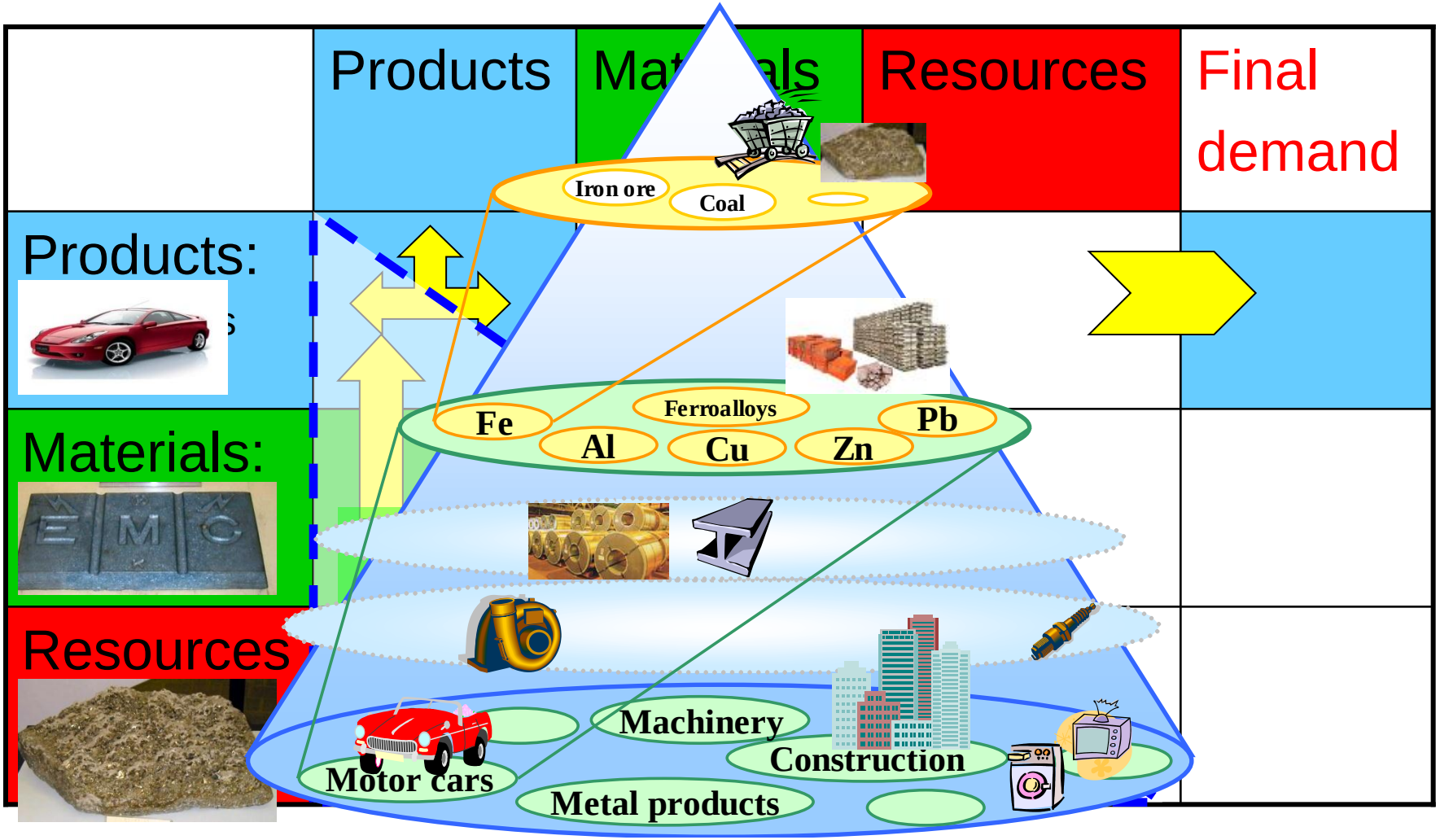
# Direct use of ferrous materials



# Final destination of ferrous materials

- Where do ferrous materials go?
- In which “final products” are ferrous materials embedded?
- Trace the flow of ferrous materials along the supply chain downward from basic materials toward final products: trace the material flow following the *stage of fabrication*.

# Triangulation of an IO matrix:
## Trace the flow of materials along fabrication stages



# WIO-MFA:

Nakamura and Nakajima; Mater. Trans. (2005),
Nakamura, Nakajima, Kondo, Nagasaka; JIE (2007)

$$\widetilde{A} = \underbrace{\Gamma}_{\text{yield filter}} \odot ( \underbrace{\Phi}_{\text{mass filter}} A)$$

$$= \begin{pmatrix} \widetilde{A}_{PP} & \widetilde{A}_{PM} & \widetilde{A}_{PR} \\ \widetilde{A}_{MP} & \widetilde{A}_{MM} & \widetilde{A}_{MR} \\ \widetilde{A}_{RP} & \widetilde{A}_{RM} & \widetilde{A}_{RR} \end{pmatrix}$$

$$= \begin{pmatrix} \widetilde{A}_{PP} & 0 & 0 \\ \widetilde{A}_{MP} & 0 & 0 \\ 0 & \widetilde{A}_{RM} & 0 \end{pmatrix}$$

# WIO-MFA:

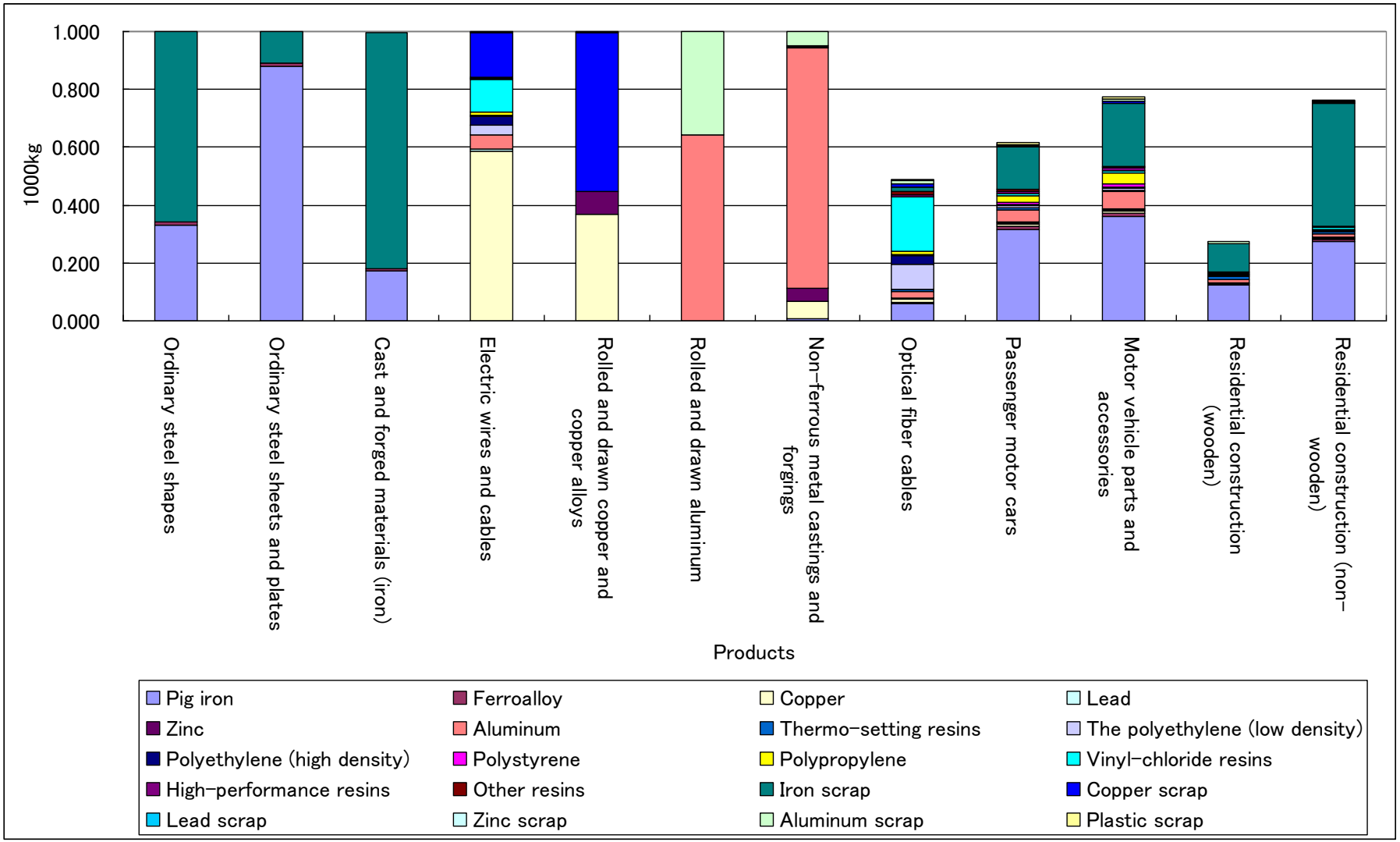
$$(I-\widetilde{A})^{-1} = \begin{pmatrix} (I-\widetilde{A}_{PP})^{-1} & 0 & 0 \\ \widetilde{A}_{MP}(I-\widetilde{A}_{PP})^{-1} & I & 0 \\ \widetilde{A}_{RM}\widetilde{A}_{MP}(I-\widetilde{A}_{pp})^{-1} & \widetilde{A}_{RM} & I \end{pmatrix}$$

$$C = \widetilde{A}_{MP}(I-\widetilde{A}_{PP})^{-1} = \widetilde{A}_{MP}\widetilde{B}_{PP}$$

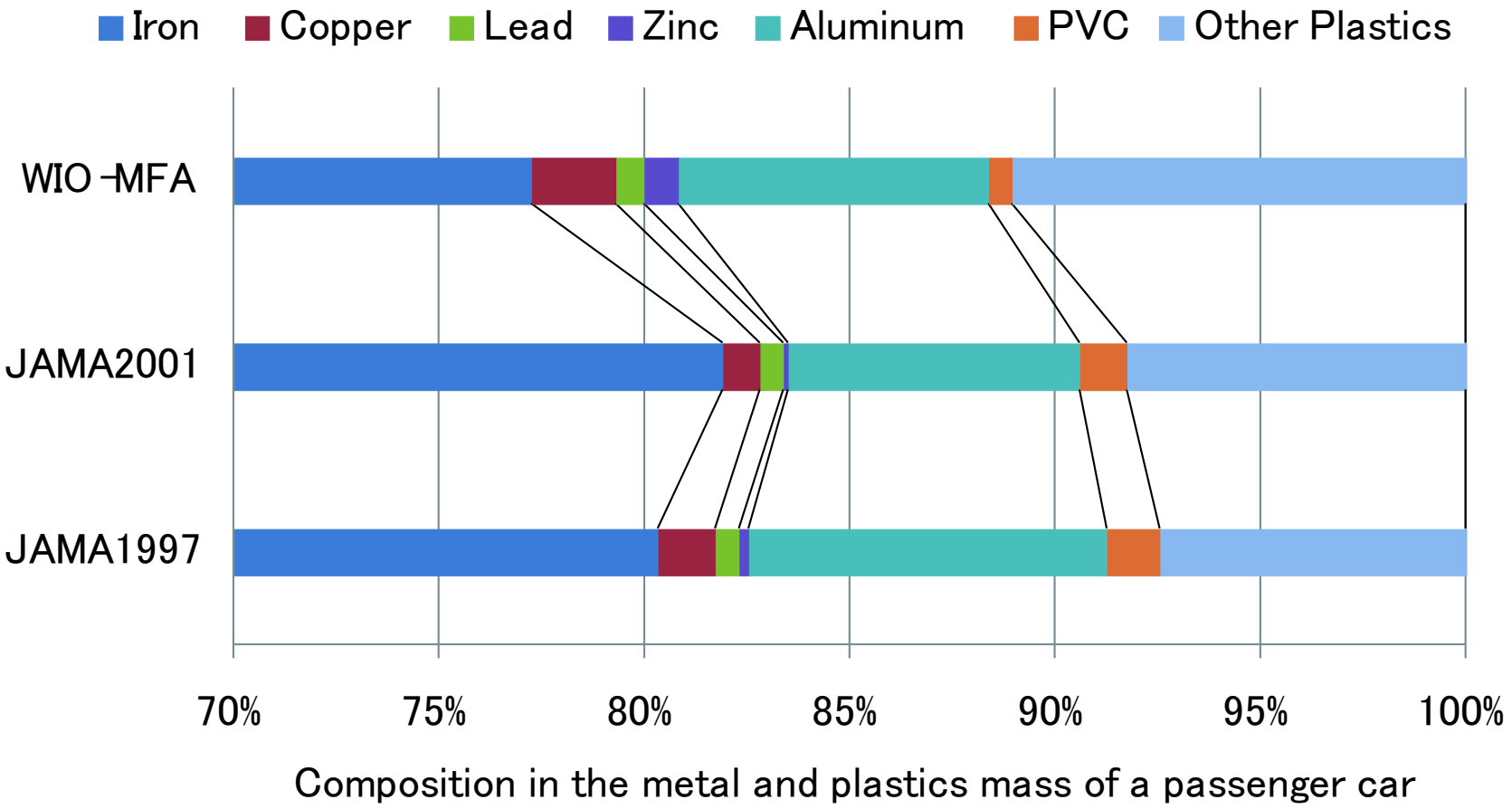
*C*: material composition matrix

*M* measured in kg => *C* in kg as well

# Metal & plastic composition of products



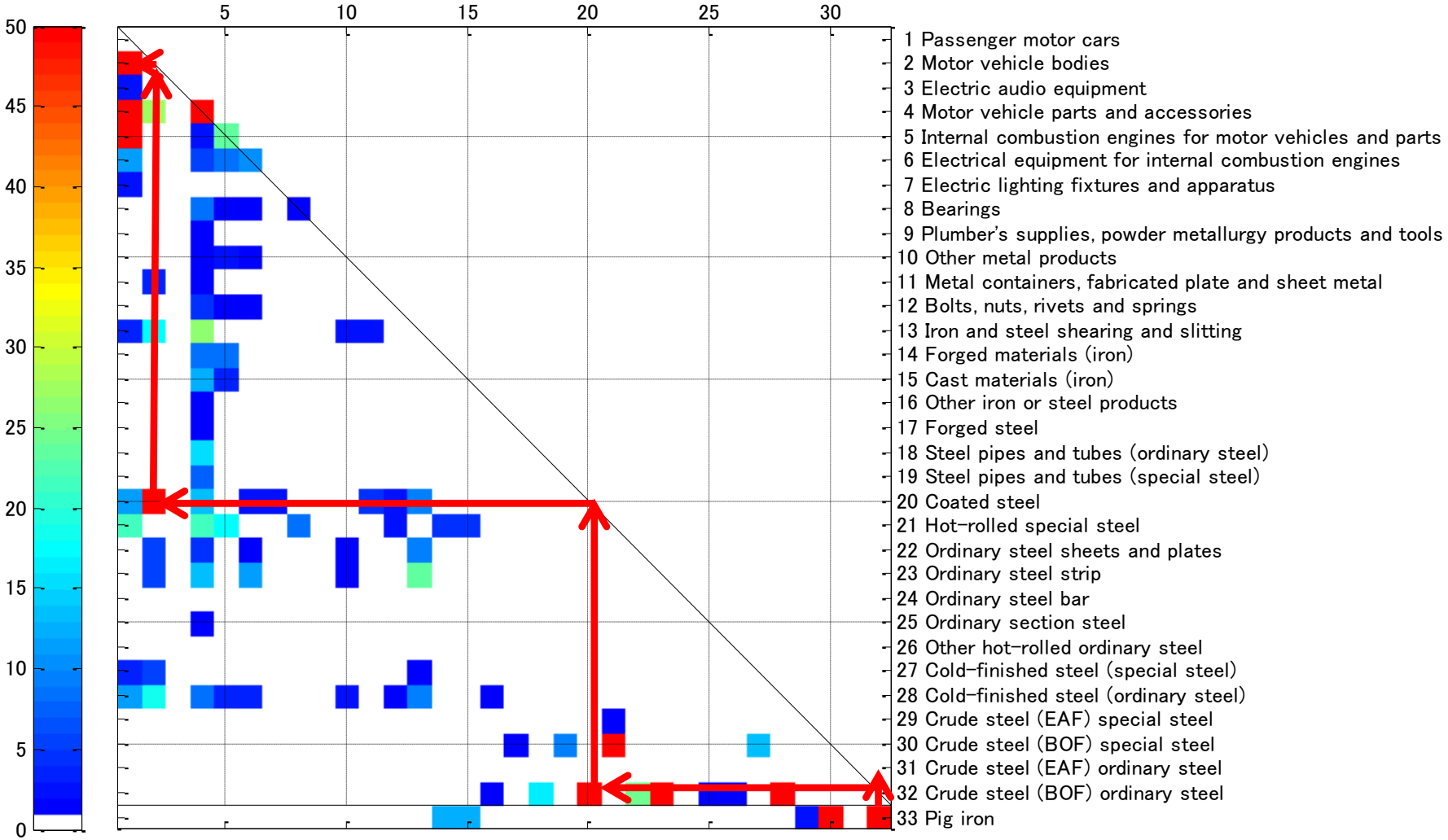
# Testing WIO-MFA



# Ferrous materials constituting a car

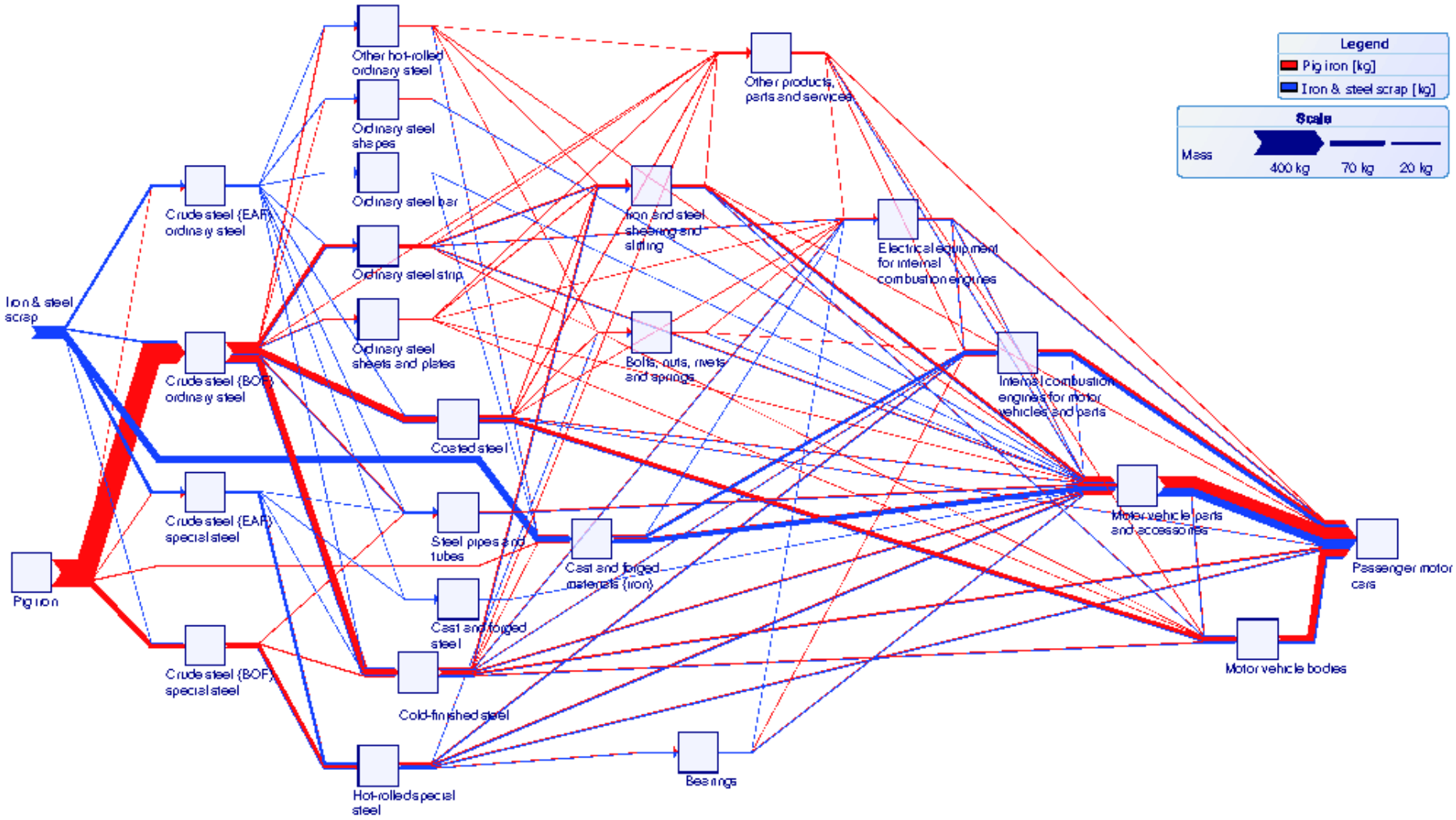
- Car consists of many parts/components
- The material composition of a car is determined by the material composition of its parts/components
- I&S scrap embedded in a car
  - Nakamura, Kondo, Matsubae, Nakajima, Nagasaka: UPIOM: A New Tool of MFA and Its Application to the Flow of Iron and Steel Associated with Car Production, ES&T 45, 2010

# IO flow of Primary Iron induced by a car




Nakamura et. al.: UPIOM: A New Tool of MFA and Its Application to the Flow of Iron and Steel Associated with Car Production, ES&T 45, 2010

# Representation of UPIOM by Sankey diagram (a composite of the two Figures)



# EoL processes of ELV



# Three types of losses:
## Amini/Castro et. al. (2007)

1. Material losses:
   - Shredder/slag losses
2. **Quality losses:**
   - No equal quality to primary iron due to mixing
3. **Dilution losses:**
   - Dilution by primary iron required in EAF due to high concentration of contaminants (Cu).

# Quantifying the losses: WIO

| | **Quality losses** | **Dilution losses** |
|---|---|---|
| Description | I&S scrap not used in BOF but in EAF | I&S scrap diluted with primary iron to meet the target quality of EAF; Cu < 0.003% |
| Scenario settings | EoL process recovers primary iron | The primary iron/scrap ratio increases in EAF<br><br>Nakamura and Yamasue *ES&T* 44, 2010 |

# Modeling based on WIO:
## S. Nakamura and E. Yamasue *ES&T* 44, 2010

The hybrid model

$$E = \begin{pmatrix} R_{\mathrm{I}} & R_{\mathrm{II}} \end{pmatrix} \begin{pmatrix} I - A_{\mathrm{I}} & -A_{\mathrm{II}} \\ -S\,G_{\mathrm{I}} & I - S\,G_{\mathrm{II}} \end{pmatrix}^{-1} \begin{pmatrix} f_{\mathrm{I}} \\ S\,w_f \end{pmatrix}$$

The functional unit

$$f_{\mathrm{I}} = \begin{pmatrix} f_{\mathrm{car}} : 1 \text{ unit of car} \\ f_{\mathrm{eaf}} : \text{EAF steel} \\ 0 \\ \vdots \\ 0 \end{pmatrix}$$

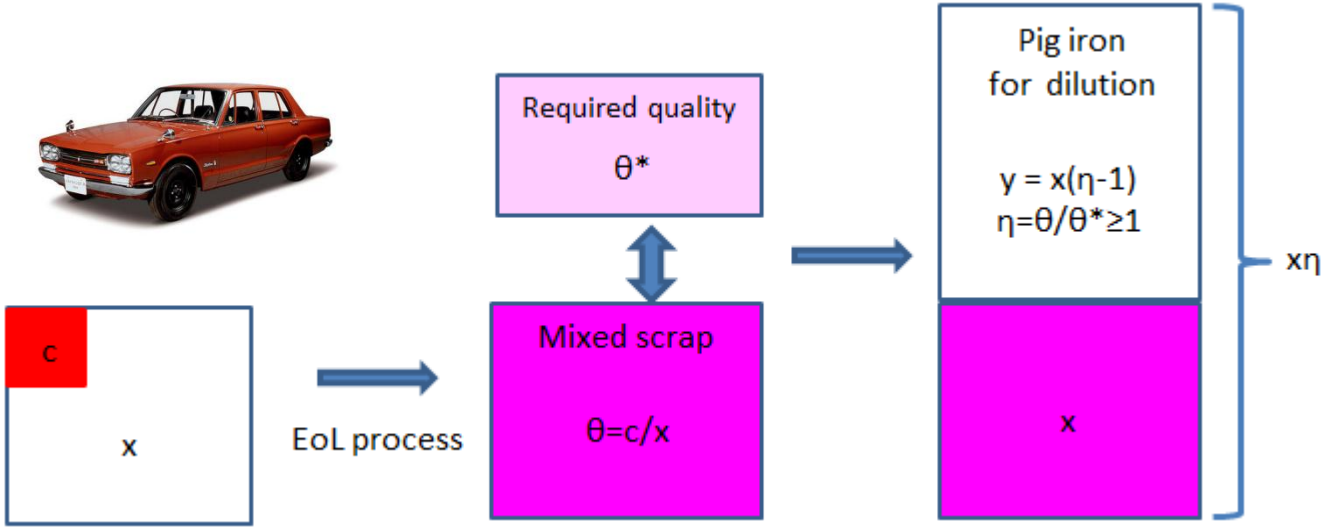
$$w_f = \begin{pmatrix} w_{\mathrm{ELV}} : 1 \text{ unit of ELV} \\ 0 \\ \vdots \\ 0 \end{pmatrix}$$

# The demand for EAF in the functional unit

- Production of a car makes little use of EAF steel => closed loop recycling of I&S scrap not possible=>system expansion
- For recycling to occur, the functional unit must include the demand for EAF steel as well.
- If dilution is required, the demand for EAF steel must include the diluted portion as well.
- Comparison of alternative scenarios under the same functional unit calls for the same amount of demand for EAF steel for the case of both with and without dilution.

# Scrap quality, dilution, and demand for EAF steel

## S. Nakamura and E. Yamasue *ES&T* 44, 2010




The EAF process

$$\begin{pmatrix} a_{\text{eaf}} \\ g_{\text{eaf}} \end{pmatrix} = \begin{pmatrix} \vdots \\ a_{\text{primary iron, eaf}} = \frac{\eta-1}{(1+\epsilon)\eta} \\ \vdots \\ -g_{\text{scrap, eaf}} = -\frac{1}{(1+\epsilon)\eta} \\ \vdots \end{pmatrix}$$

$\epsilon$ : portion of other inputs

# Avoiding mixing. How?

- Classify scrap types based on chemical composition
- Design for disassembly (DfD): joints/liberation of materials ADF
- “Smart” sorting processes

***Thank you for your attention***

*For further inquiry or questions, please visit*

**www.f.waseda.jp/nakashin/**