Tracking metal flow network using hybrid Ghoshian framework

Sangwon Suh

Bren School of Environmental Science and Management
University of California in Santa Barbara


Metals, where are you going?

Agenda

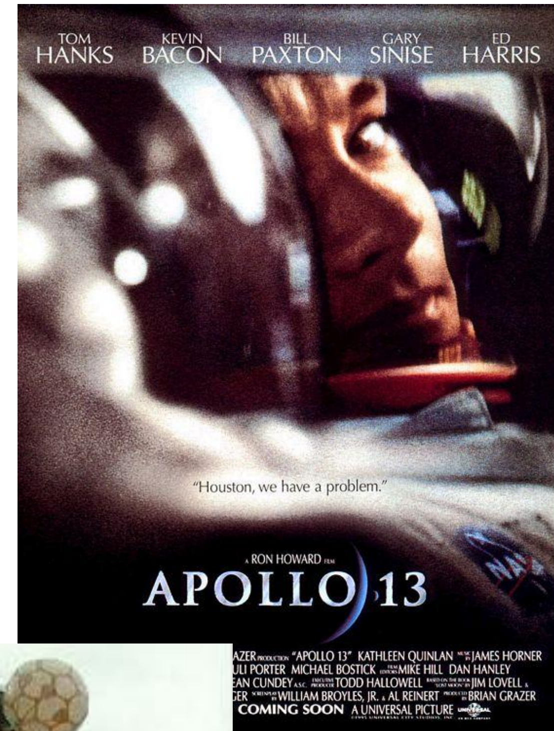
1. Introduction to Industrial Ecology
2. Background and objectives
3. Method
4. Results
5. Conclusions and discussion

1. Introduction to Industrial Ecology

Biochemical cycles are the building-blocks of the earth's life-supporting system

Ecosphere®

Spaceship Earth: how vulnerable is the technosphere against sudden discontinuation of supplies from the environment?



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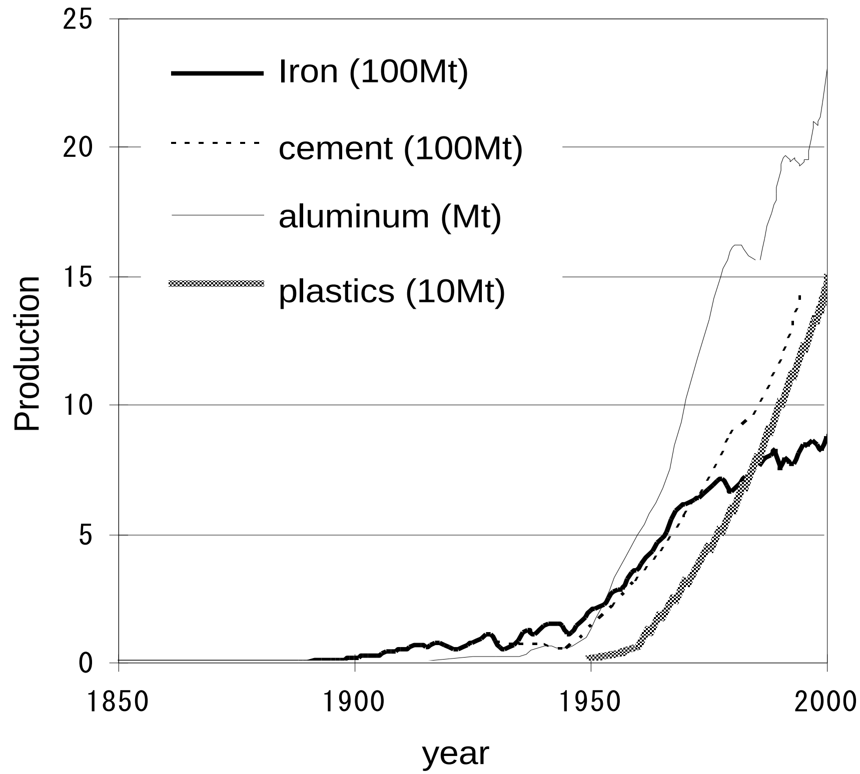
Human use of materials



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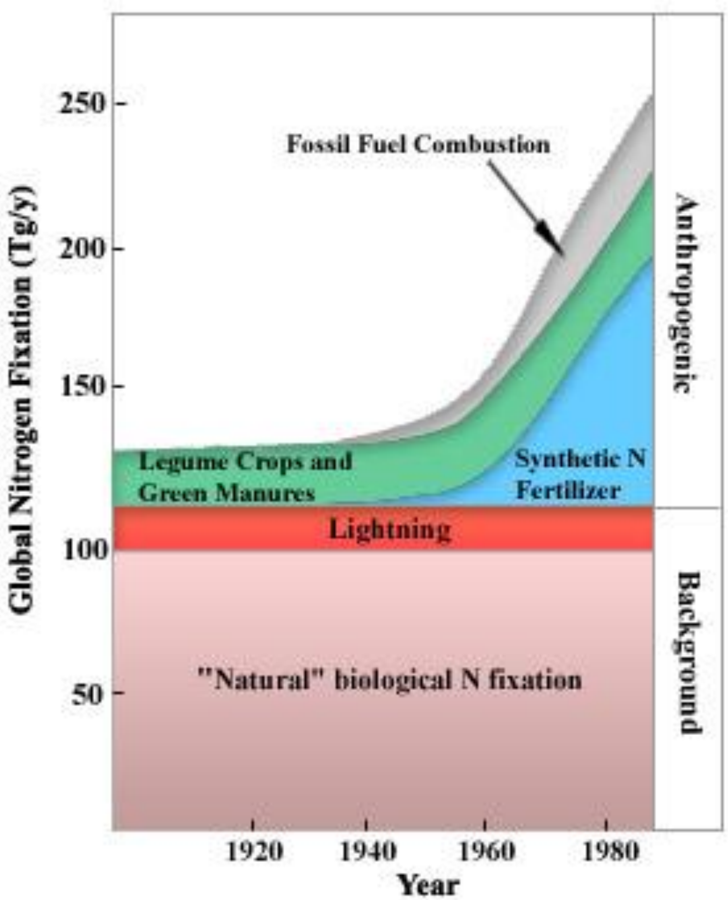
Source: Halada (2006) *Hidden material flow of metal behind economics*, Tokyo, Japan.

Nutrient flows and hypoxia



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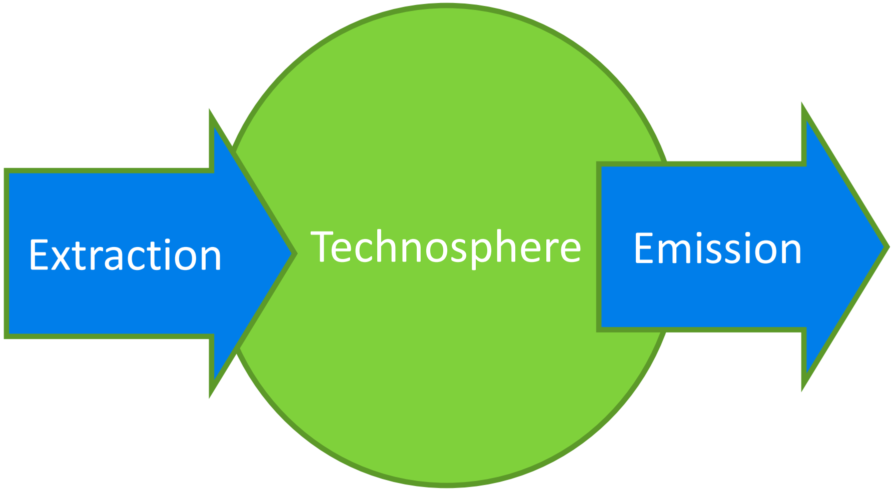
Source: Vitousek, P. M., Matson, P. A. (1993) Agriculture, the global nitrogen cycle, and trace gas flux. The Biogeochemistry of Global Change: Radiative Trace Gases. R. S. Oremland. New York, Chapman and Hall

Industrial Ecology: closing the loop

- In principle, adverse impacts by humans can be prevented from the source by closing the materials cycle within the technosphere.



Industrial ecology

- Derived from "industrial ecosystem" coined by Frosch and Gallopoulos (1989).
- Field of study concerns stocks and flows of materials and energy in human-nature complexity.

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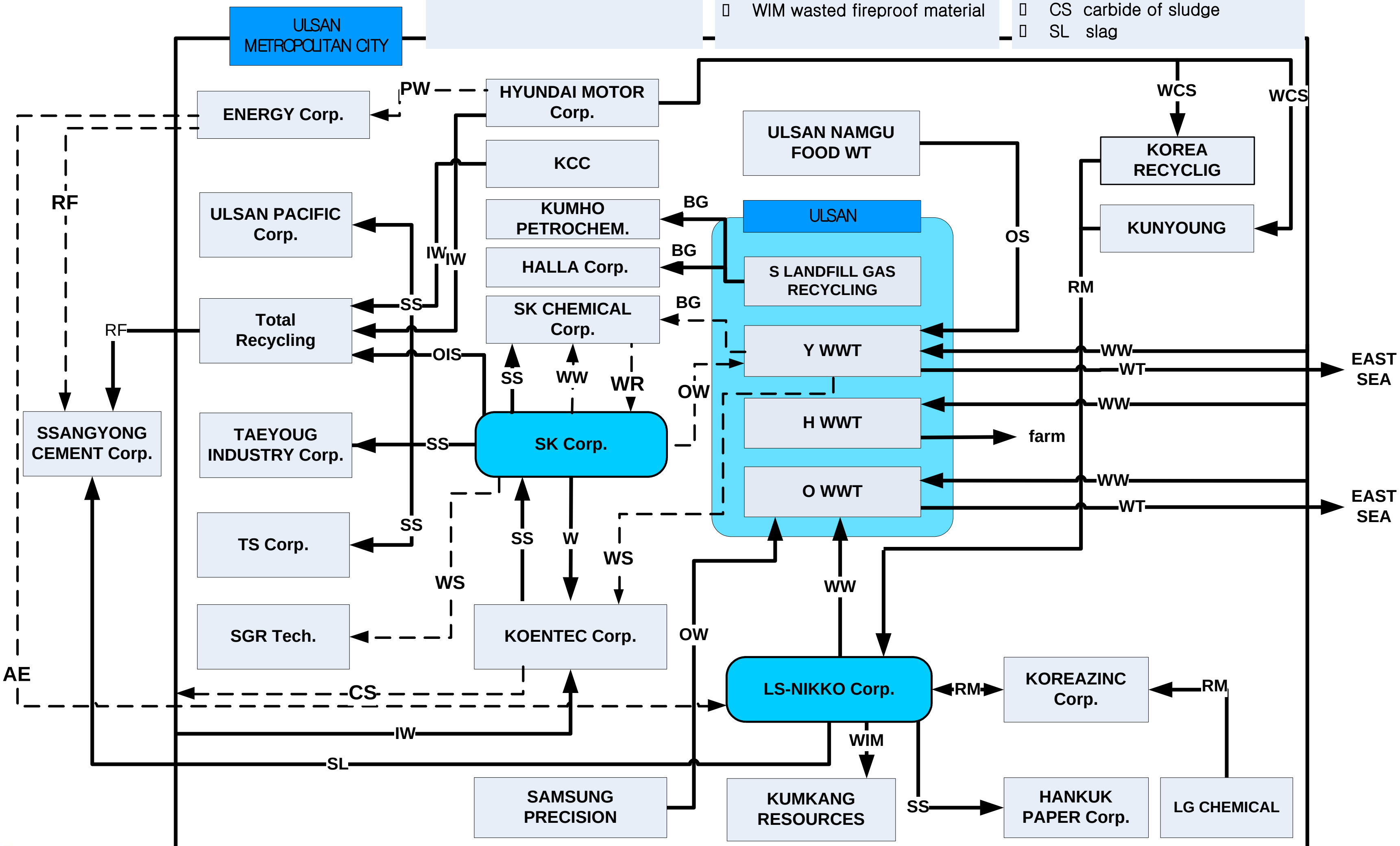
Frosch, R.A.; Gallopoulos, N.E. (1989). Strategies for Manufacturing. *Scientific American* 261 (3): 144–152

- W pure water
- WW wastewater influent
- OW organic wastewater
- WT WW effluent
- WR WW reusing

- IW industrial waste
- PW wasted plastic
- WS wasted sludge
- OS organic sludge
- OIS oil sludge
- WCS wasted casting sand
- WIM wasted fireproof material

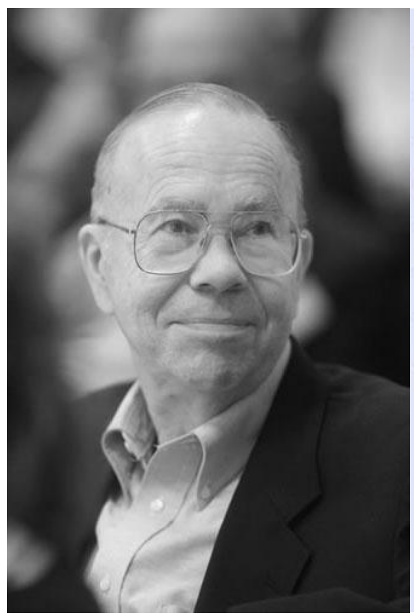
- AE alternative energy
- BG biogas
- RF recovery fuel production
- SS steam production & sale
- C catalysis
- RM valuable metal recovery
- CS carbide of sludge
- SL slag

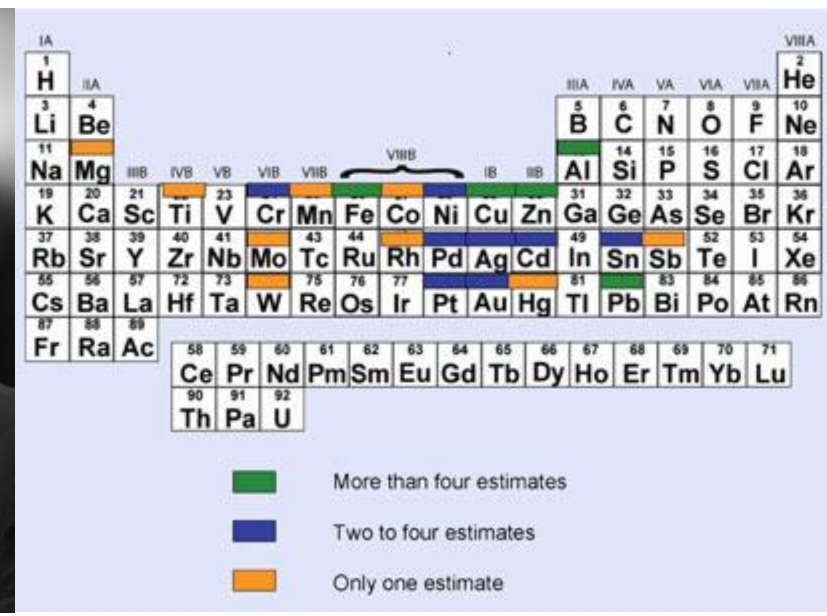


Recycling rate

- Little is known
- Only a few metals exceed 50%, many <1%

International Panel
for Sustainable
Resource Management





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Graedel, T. et al. (2011) Metal stocks in society and recycling rates, International Panel for Sustainable Resources Management, UNEP, Paris, France.

Urban mining

1 ton

=

150 g

100 kg

2. Background and ojbectives

Background and objectives

- With the rising raw materials price, in 2007 S. Korean government initiated a project to identify
  - Materials efficiency improvement opportunities
  - Urban mining opportunities
- Systematic material flow data infrastructure is lacking in S. Korea

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Question

- Can a screening analysis on urban metal stock be made with limited resources using readily available information?
- What are the structures and pathways of major metals in South Korean economy?
- Where do these metals end up?
- What are the modeling choices?

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3. Method

3.1. Overview
3.2. Markov chain
3.3. Supply and demand driven IO
3.4. Markov chain revisited

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Methodology

- Target metals:
  - Lead (Pb), Zinc (Zn), Manganese (Mn), Aluminum (Al), and Molybdenum (Mo).
- Survey of available information
  - Input-Output Tables
  - Domestic extraction data
  - Import and export statistics
  - Point data on particular metal flows

Methodology

- Making the best use of existing data
  - Puzzle making
  - Sufficiency principle
- Use of Ghoshian framework
  - Distribution of materials
- Hybrid approach
  - Use of both physical and monetary quantities
  - Use of both company-supplied and IO data

Time-series supply-driven model

- Suh (2005) demonstrated that supply-driven models works well in describing physical flows.
- Modified Ghoshian framework:
  - Disaggregation of sectors (ex: Lead and Zinc)
  - Adding waste, scrap, increase in stock
  - Reflecting physical quantities
  - Distinguishing material and non-material products

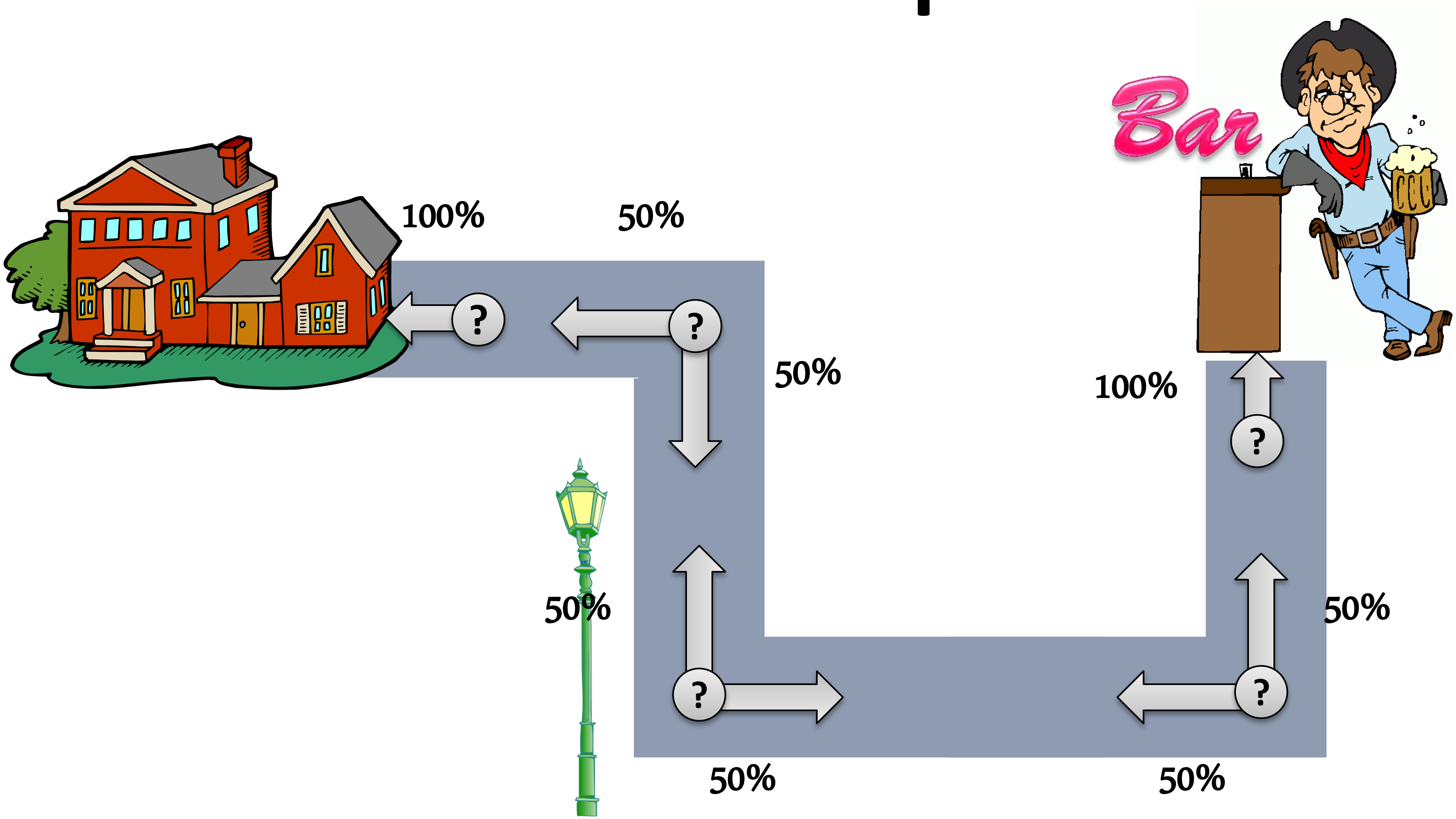
Suh, S., 2005: Theory of Materials and Energy Flow Analysis in Ecology and Economics, *Ecological Modeling*, 189 251 – 269.

3.2. Markov chain

Absorbing Markov chain

- Andrey Markov (1856 – 1922): Russian mathematician
- Concerns how an initial state of a system eventually arrives at a final (absorbing) state.
- Illustrated using the famous “drunkard walk” problem.

Drunkard walk problem



Transient matrix, *P*

$$P = \begin{array}{c} \\ 0 \\ 1 \\ 2 \\ 3 \\ 4 \end{array} \begin{array}{c} \begin{array}{ccccc} 0 & 1 & 2 & 3 & 4 \end{array} \\ \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 1/2 & 0 & 1/2 & 0 & 0 \\ 0 & 1/2 & 0 & 1/2 & 0 \\ 0 & 0 & 1/2 & 0 & 1/2 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \end{array}$$

- Canonical form

$$P = \begin{array}{c} \\ \text{TR.} \\ \text{ABS.} \end{array} \begin{array}{c} \begin{array}{cc} \text{TR.} & \text{ABS.} \end{array} \\ \left(\begin{array}{c|c} Q & R \\ \hline 0 & I \end{array}\right) \end{array} = \begin{array}{c} \\ 1 \\ 2 \\ 3 \\ 0 \\ 4 \end{array} \begin{array}{c} \begin{array}{ccccc} 1 & 2 & 3 & 0 & 4 \end{array} \\ \left(\begin{array}{ccc|cc} 0 & 1/2 & 0 & 1/2 & 0 \\ 1/2 & 0 & 1/2 & 0 & 0 \\ 0 & 1/2 & 0 & 0 & 1/2 \\ \hline 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{array}\right) \end{array}$$

Solution

$$N = (I - Q)^{-1} = \begin{array}{c} \\ 1 \\ 2 \\ 3 \end{array}\begin{array}{c} \begin{array}{ccc} 1 & 2 & 3 \end{array} \\ \begin{pmatrix} 3/2 & 1 & 1/2 \\ 1 & 2 & 1 \\ 1/2 & 1 & 3/2 \end{pmatrix} \end{array}$$

- Absorption probability, *B*

$$B = NR = \begin{pmatrix} 3/2 & 1 & 1/2 \\ 1 & 2 & 1 \\ 1/2 & 1 & 3/2 \end{pmatrix} \begin{pmatrix} 1/2 & 0 \\ 0 & 0 \\ 0 & 1/2 \end{pmatrix}$$

$$= \begin{array}{c} \\ 1 \\ 2 \\ 3 \end{array}\begin{array}{c} \begin{array}{cc} 0 & 4 \end{array} \\ \begin{pmatrix} 3/4 & 1/4 \\ 1/2 & 1/2 \\ 1/4 & 3/4 \end{pmatrix} \end{array} .$$

Absorbing Markov chain

- Used for many applications including multi-media fate-and-transport modeling of pollutants, modeling microbial activities, voting propensity analysis, etc.
- Has inherent similarities with IO frameworks:
  - I will come back on this later.

3.3. Demand and supply-driven IO frameworks

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Demand-driven model

$$\begin{bmatrix} z_{11} & \cdots & z_{1n} \\ \vdots & \ddots & \vdots \\ z_{n1} & \cdots & z_{nn} \end{bmatrix} \begin{bmatrix} y_1 \\ \vdots \\ y_n \end{bmatrix}$$

- Row-wise balance

$$\sum_j z_{ij} + y_i = x_i$$

Intermediate consumption

Final consumption

Output

- In

$$Zi + y = x$$

if $A = Z\hat{x}^{-1}$ (column-wise coefficient matrix)

$$Ax + y = x$$

$$x = (I - A)^{-1}y$$ (demand-driven primal)

Supply-driven model

- Column-wise balance

$$\sum_i z_{ij} + v_j = x_j$$

$$\begin{bmatrix} z_{11} & \cdots & z_{1n} \\ \vdots & \ddots & \vdots \\ z_{n1} & \cdots & z_{nn} \end{bmatrix}$$
$$\begin{bmatrix} v_1 & \cdots & v_n \end{bmatrix}$$

Intermediate inputs

Value added

Output

- In

$$i'Z + v = x'$$

if $B = \hat{x}^{-1}Z$ (row-wise coefficient matrix)

$$x'B + v = x'$$

$$x' = v(I - B)^{-1}$$ (supply-driven primal)

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Ghoshian framework for monetary system

- Ghosh, Ambica (1958) "Input-output approach to an allocative system" *Econometrica*.
- Based on the supply-driven model (column-wise balancing = row-wise coefficient matrix).
- Discussion followed by
  – Oosterhaven (1988, 1989, 1996), Dietzenbacher (1989, 1997), Miller (1989), Sonis and Hewings (1992), de Mesnard (1997, 2002, 2008).

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Ghosh (1958): interpretation

- Dietzenbacher (1997) interpreted the Ghosh (1958) as a cost-push mechanism
  - How an increase in price of a factor input is passed onto the consuming sectors.
- But generally, the literature is rather critical about Ghosh (1958) as an economic model because…

It doesn't work!

- Suppose a row-wise coefficient matrix (monetary):

B	**Iron ore**	**Steel**	**Motor vehicle**
Iron ore	0	0.5	0
Steel	0	0	0.1
Motor vehicle	0	0.1	0

$$x' = v(I - B)^{-1} = v + vB + vB^2 + \cdots$$

If $v = (1 \quad 0 \quad 0)$

$$x' = (1 \quad 0 \quad 0) + (1 \quad 0 \quad 0)\begin{pmatrix} 0 & 0.5 & 0 \\ 0 & 0 & 0.1 \\ 0 & 0.1 & 0 \end{pmatrix} + \ldots$$

Works as if the iron ore is the only limiting factor: violates non-substitution

If $v = (2 \quad 0 \quad 0)$

$$x' = (2 \quad 0 \quad 0) + (2 \quad 0 \quad 0)\begin{pmatrix} 0 & 0.5 & 0 \\ 0 & 0 & 0.1 \\ 0 & 0.1 & 0 \end{pmatrix} + \ldots$$

But it mimics the propagation of cost push toward the downstream.

Nevertheless…

- I would argue two things:

  1. The supply-driven model works fine for describing ***ex-post*** flows of physical quantities.

  2. Physical version of the supply-driven model is equivalent to Markov chain model.

3.4. Markov chain revisited

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Physical IO system

	Intermediate	Waste treatment	Final demand
Intermediate	*Z*	*s*	y
Resource input	*r*		
Waste	*w*		

Supply-driven model becomes:

$$x' = (r - w)(I - B)^{-1}$$

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- Suppose a row-wise coefficient matrix (for iron flow):

B	**Iron ore**	**Steel**	**Motor vehicle**
Iron ore	0	0.5	0
Steel	0	0	0.1
Motor vehicle	0	~~0.1~~ **0**	0

$$x' = (r - w)(I - B)^{-1} = (r - w)(I + B + B^2 + \cdots)$$

If $r - w = (1 \quad 0 \quad 0)$

$$x' = (1 \quad 0 \quad 0) + (1 \quad 0 \quad 0)\begin{pmatrix} 0 & 0.5 & 0 \\ 0 & 0 & 0.1 \\ 0 & 0 & 0 \end{pmatrix} + \ldots$$

If $r - w = (2 \quad 0 \quad 0)$

$$x' = (2 \quad 0 \quad 0) + (2 \quad 0 \quad 0)\begin{pmatrix} 0 & 0.5 & 0 \\ 0 & 0 & 0.1 \\ 0 & 0 & 0 \end{pmatrix} + \ldots$$

Supply-driven model shows the cumulative materials passed onto the next stage.

Limited applicability as an ex-ante model, but describing ex-post material flow works well.

Observations

- Supply-driven physical model can describe the *ex-post* cumulative resources passed onto the consuming sectors.
- But such an analysis does not necessarily require supply-driven model.
- What makes supply-driven model useful is its ability to show the intermediate resource flows (will come back on that).

Physical supply-driven model closed toward waste and final demand

*B**	Iron ore	Steel	Motor vehicle	waste	Final demand
Iron ore	0	0.5	0	0.5	0
Steel	0	0	0.1	0.3	0.6
Motor vehicle	0	0	0	0.2	0.8
Scrap	0	0	0	0	0
Final demand	0	0	0	0	0

Physical supply-driven model closed toward waste and final demand

*B**	Iron ore	Steel	Motor vehicle	waste	Final demand
Iron ore Steel Motor vehicle		B_1		B_2	
Scrap Final demand		0		0	

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Physical supply-driven model closed toward waste and final demand

*B**	Iron ore	Steel	Motor vehicle	waste	Final demand
Iron ore					
Steel					
Motor vehicle			*B**		
Scrap					
Final demand					

Ghosh inverse

Waste and final demand portion

$$(I - B^*)^{-1} = \begin{pmatrix} I - B_1 & -B_2 \\ 0 & I \end{pmatrix}^{-1} = \begin{pmatrix} (I - B_1)^{-1} & \overbrace{(I - B_1)^{-1} B_2}^{\text{Waste and final demand portion}} \\ 0 & I \end{pmatrix}$$

- Recall that the Markovian canonical form was:

$$P = \begin{array}{c} \\ \text{TR.} \\ \text{ABS.} \end{array} \begin{array}{c} \begin{array}{cc} \text{TR.} & \text{ABS.} \end{array} \\ \left(\begin{array}{c|c} Q & R \\ \hline 0 & I \end{array} \right) \end{array}$$

and that the chance of final absorption was given by $(I - Q)^{-1}R$

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Observations

- Absorbing Markov chain is works as a supply-driven physical IO model.
- Furthermore, if there is no waste, the total embodied resource calculated by physical Leontief primal equals the material content in the final demand and waste.
  - Proof is simple and left to the readers.

Network of resource distribution

- From the supply-driven model, one can derive a matrix of resource flow (not embodiment) network, *M* such that

$$M = \widehat{G_{i,*}}B$$

$G_{i,*}$ is the ith row of the Ghosh inverse, $(I - B)^{-1}$

- *Output Environ* analysis by Patten (1982)*

* Patten, B.C., 1982. Environs—relativistic elementary-particles for ecology. Am. Natural. 119, 179–219.

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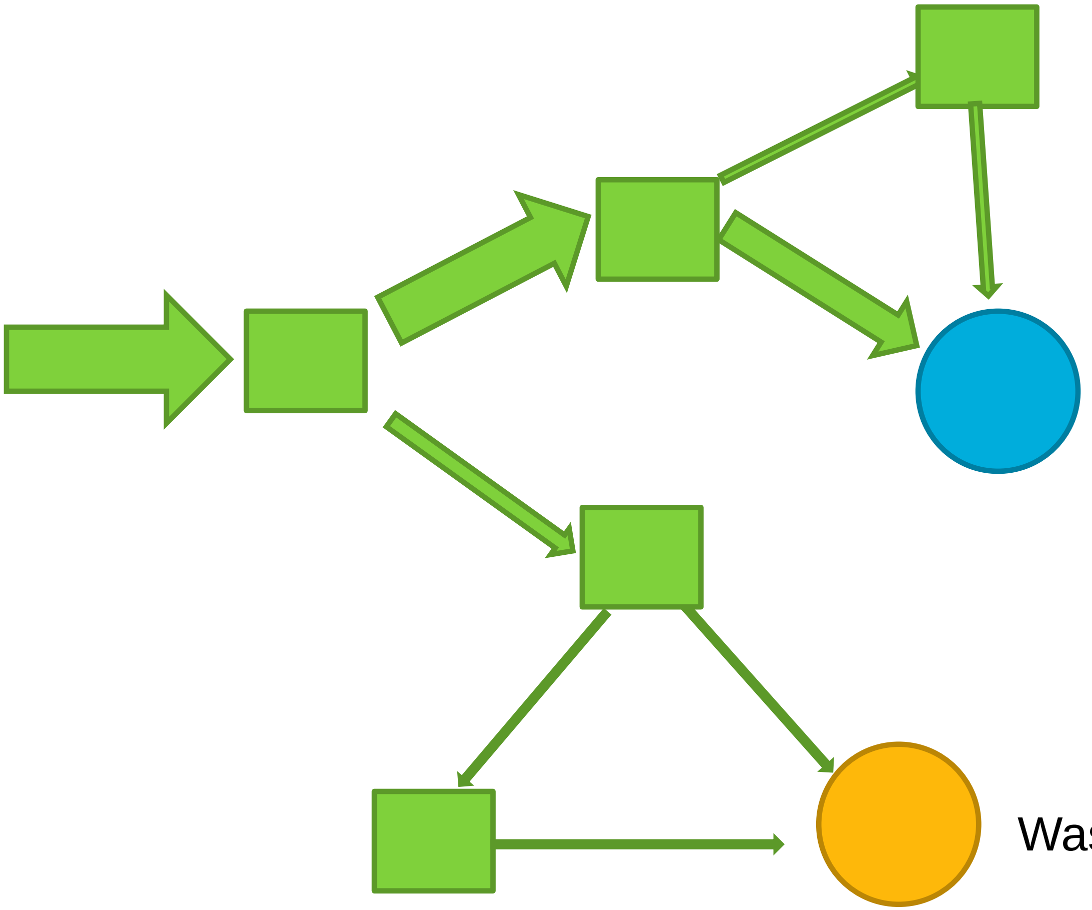
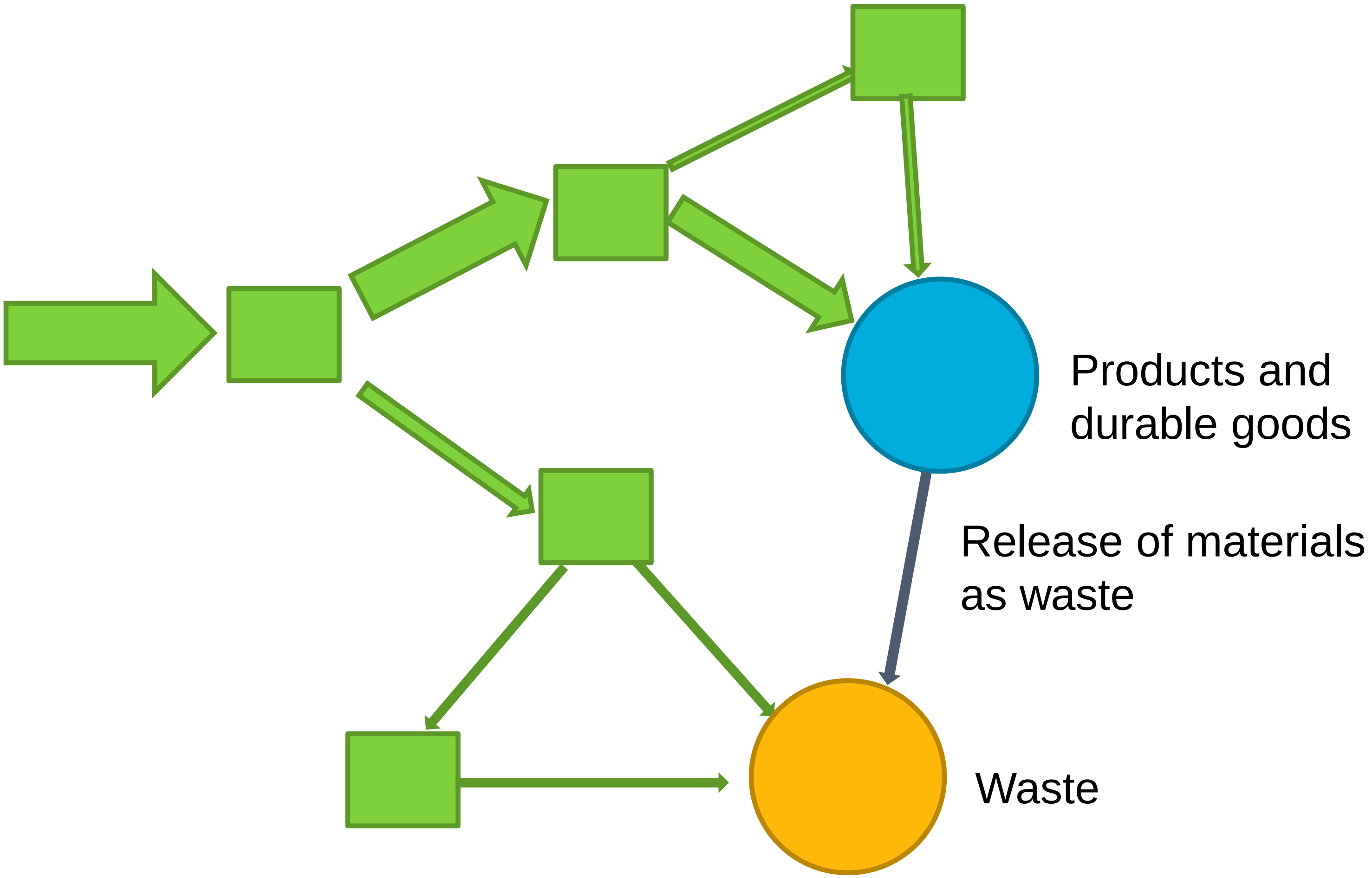
See: Suh, S., 2005: Theory of Materials and Energy Flow Analysis in Ecology and Economics, *Ecological Modeling*, 189 251 – 269.

How it works?

Year 1

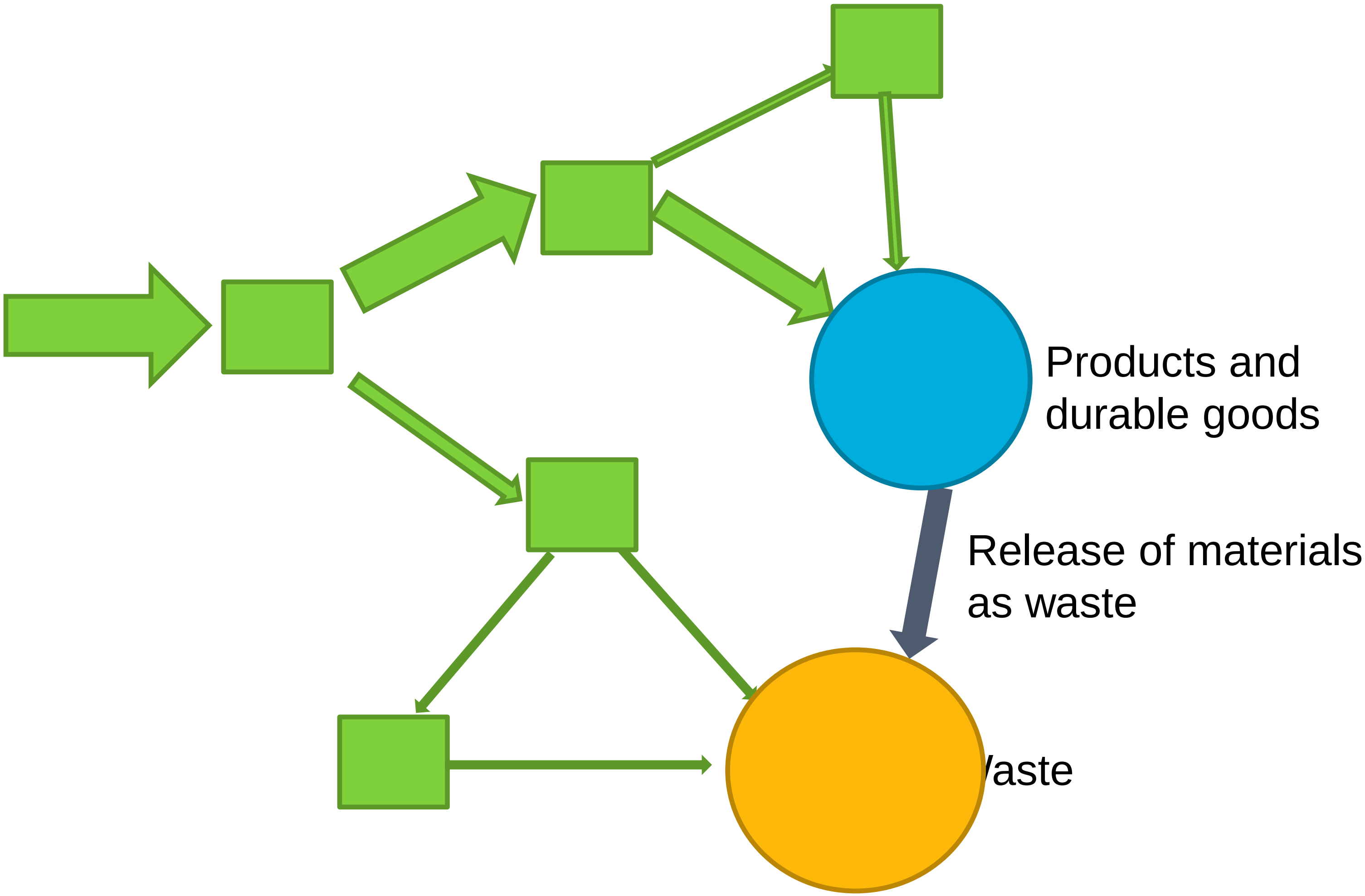


Year 2



Products and durable goods
Release of materials as waste
Waste

Year 3



Products and durable goods
Release of materials as waste
/aste

4. Results

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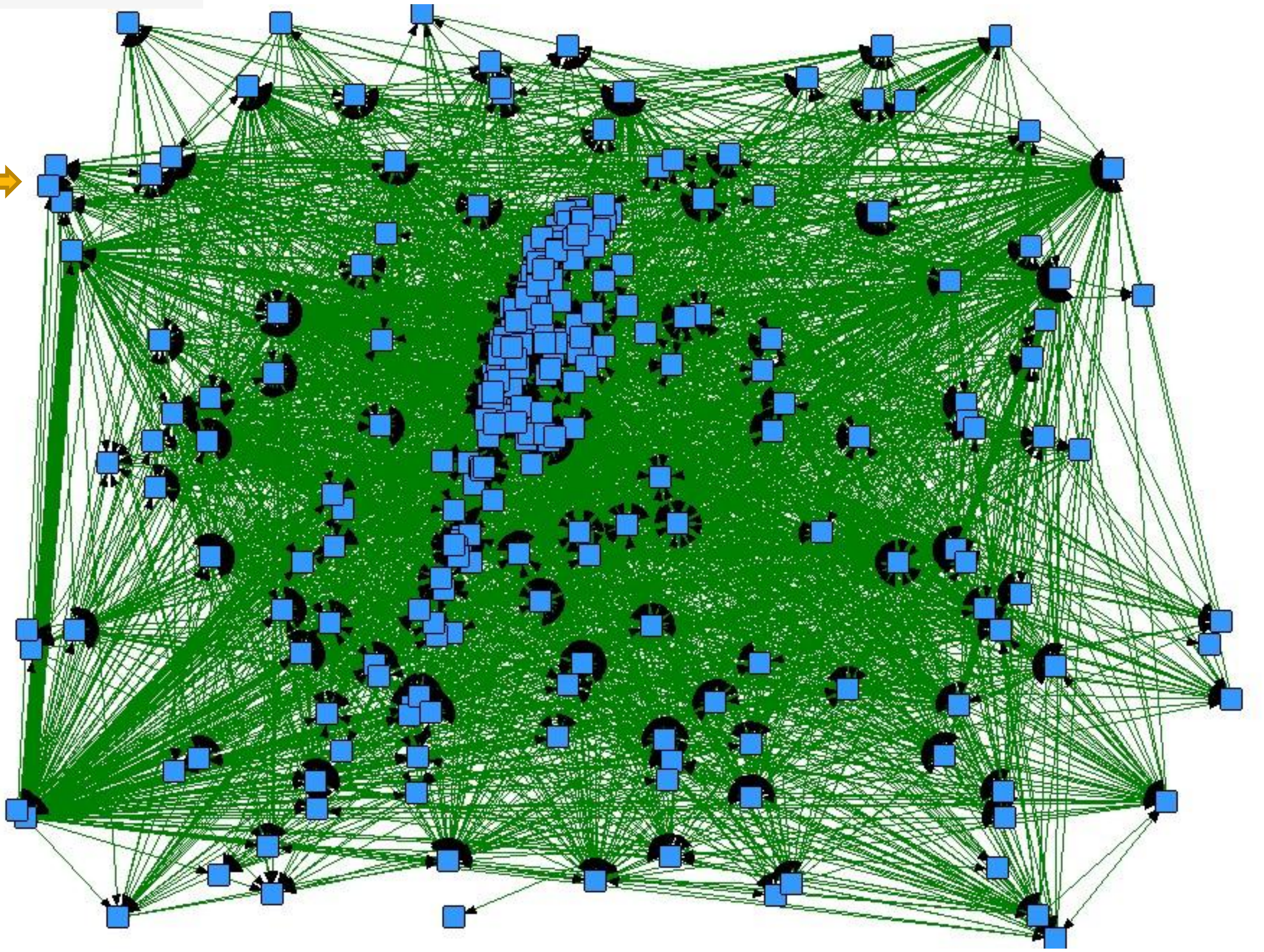
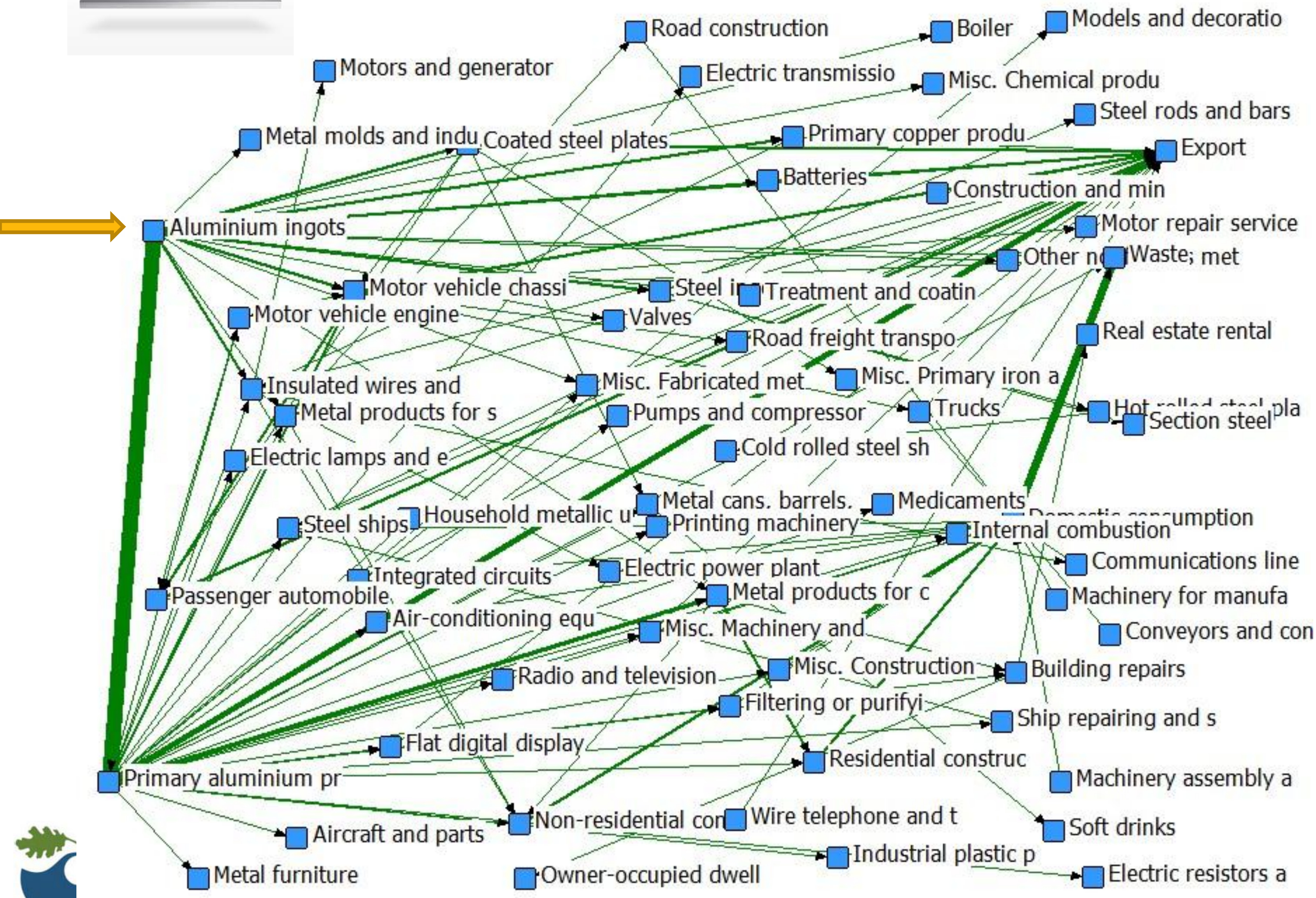
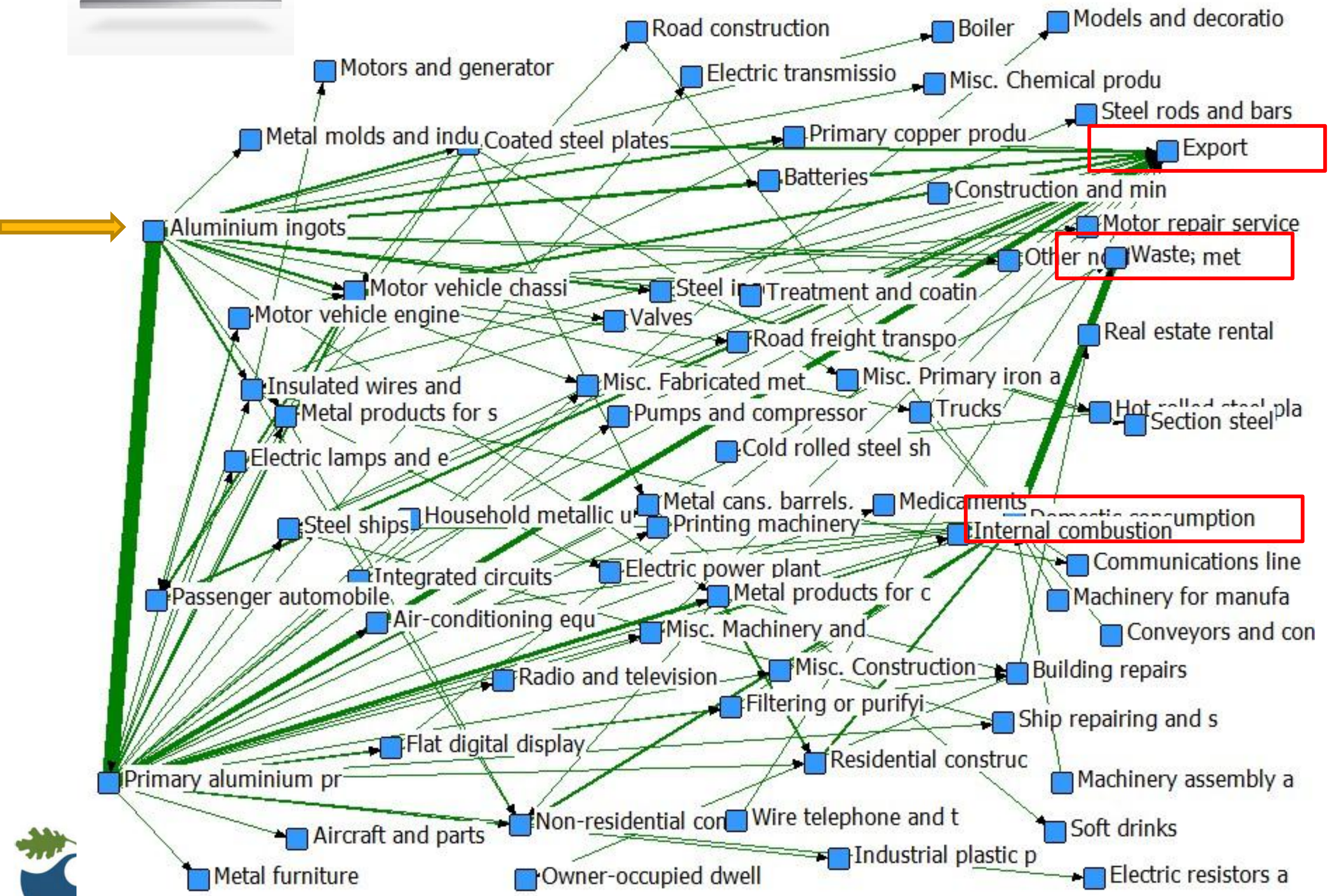
Aluminum 90% of the total flow (2007)



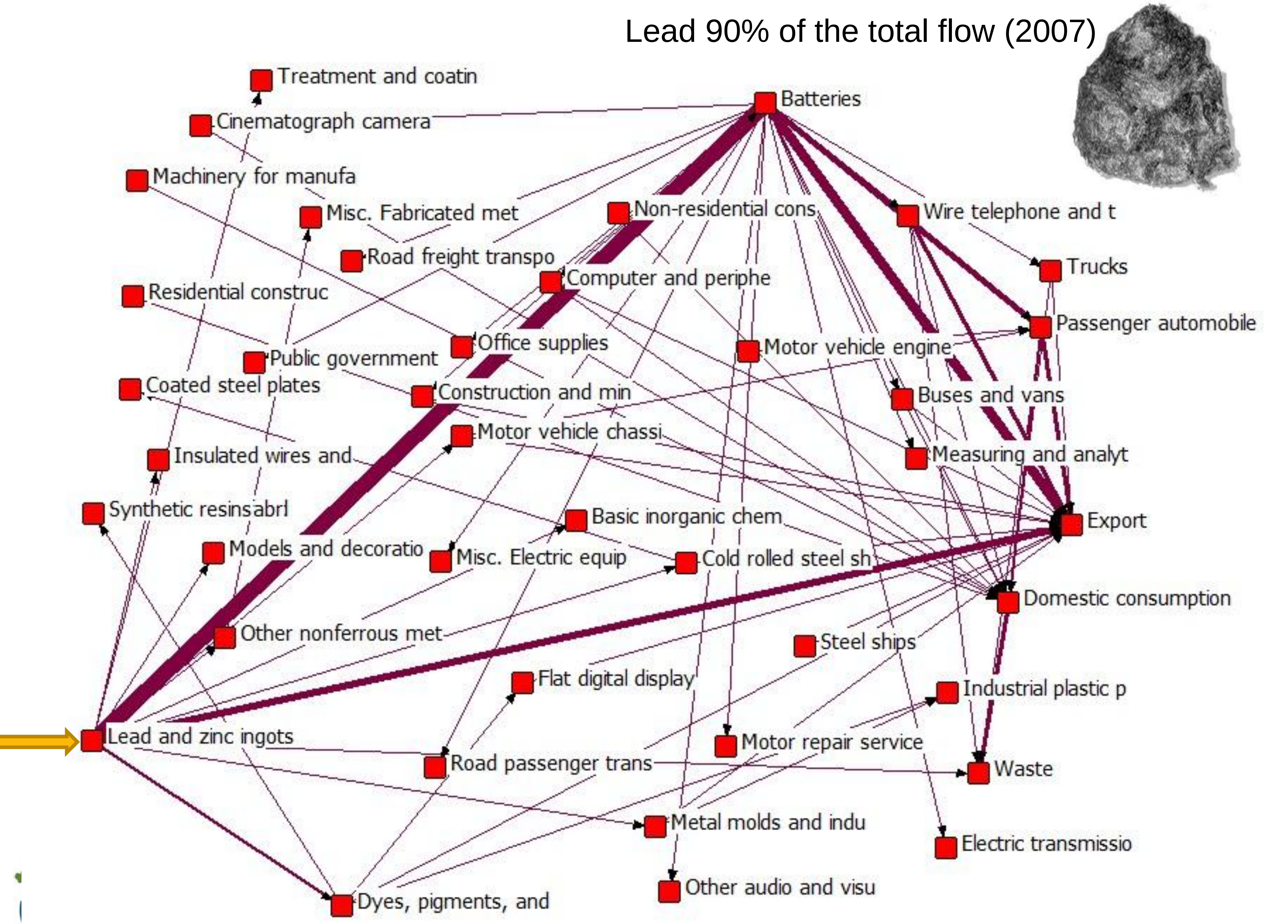
Aluminum 80% of the total flow (2007)



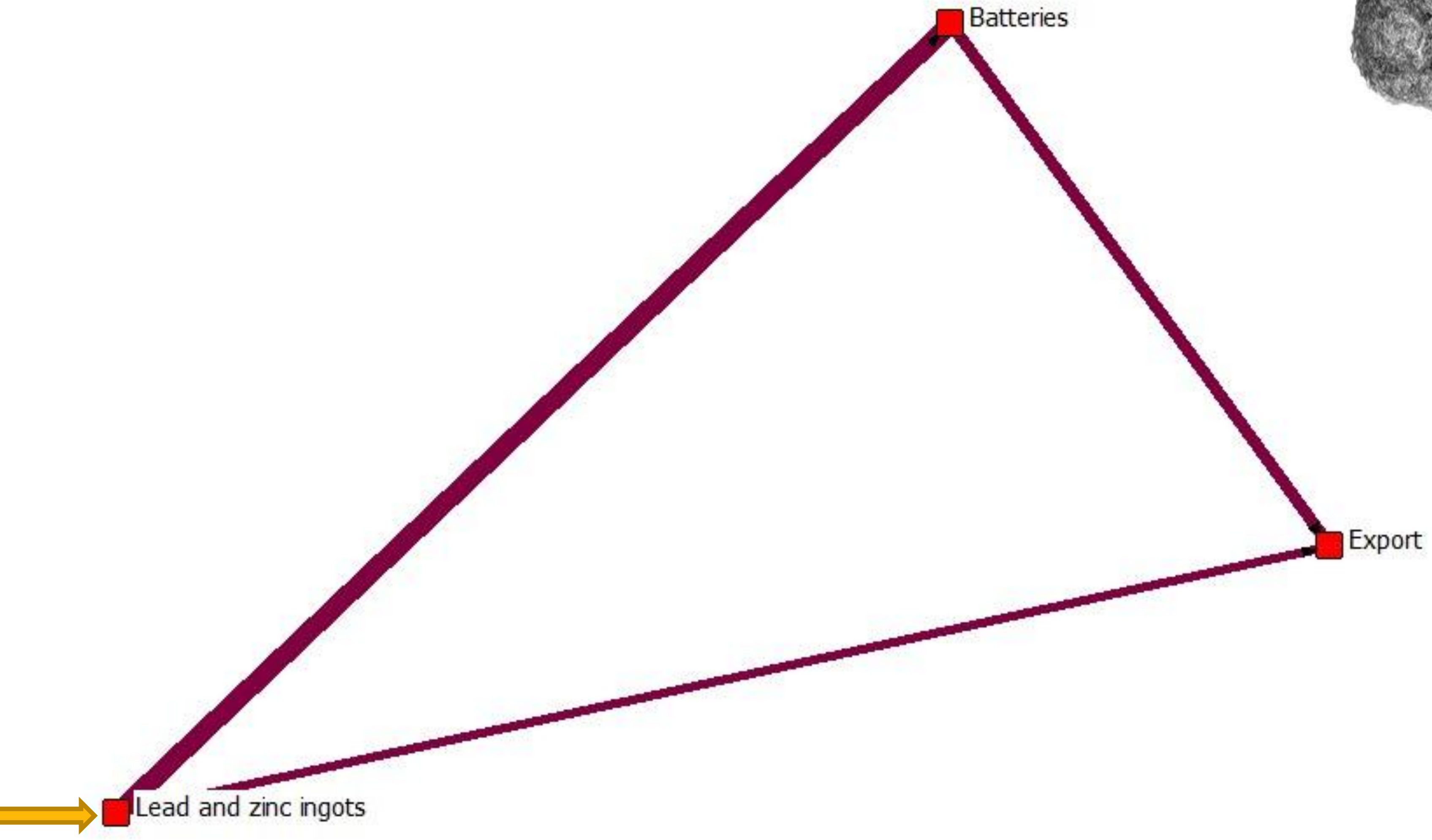
Aluminum 20% of the total flow (2007)



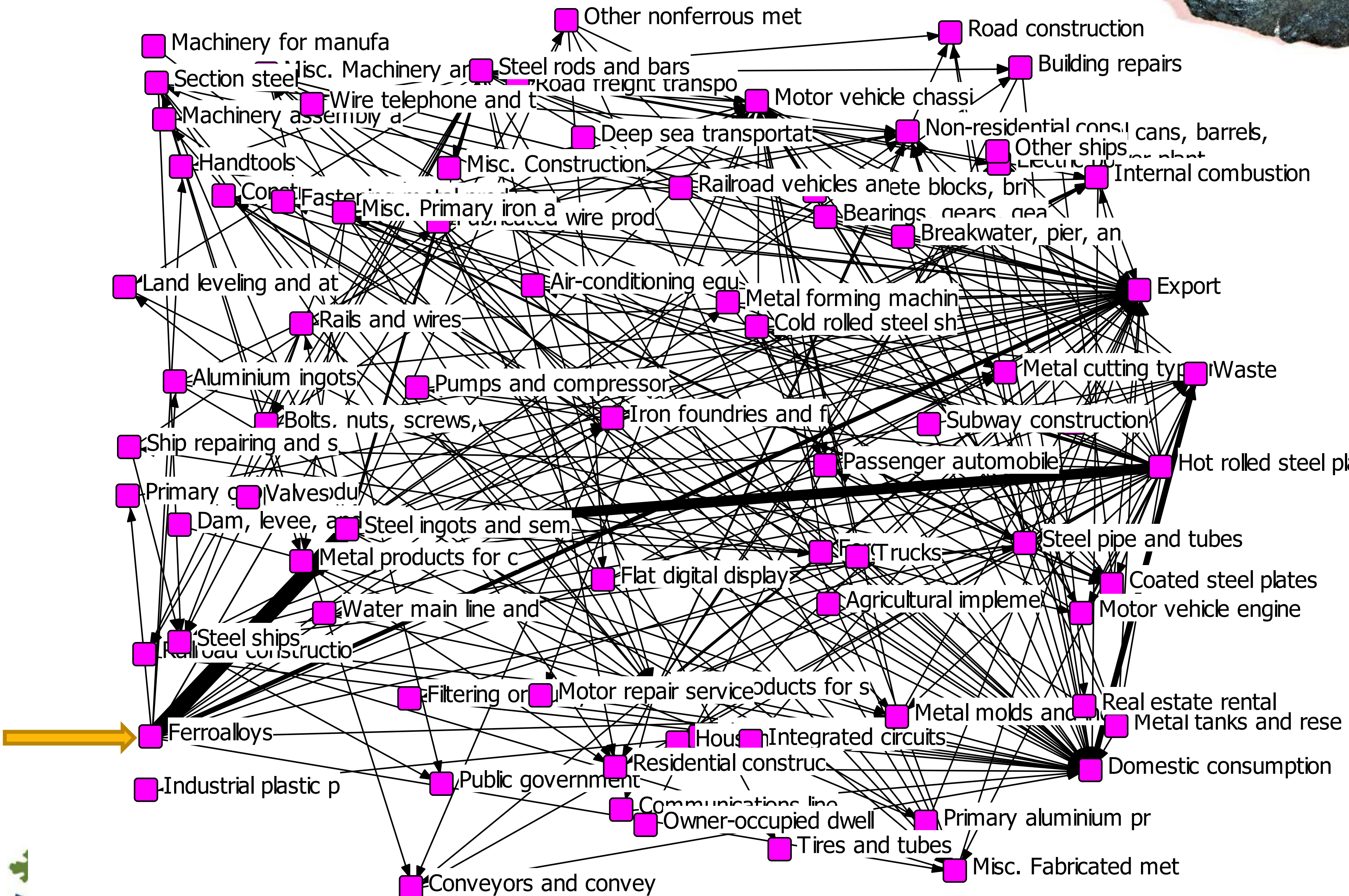
Lead 90% of the total flow (2007)



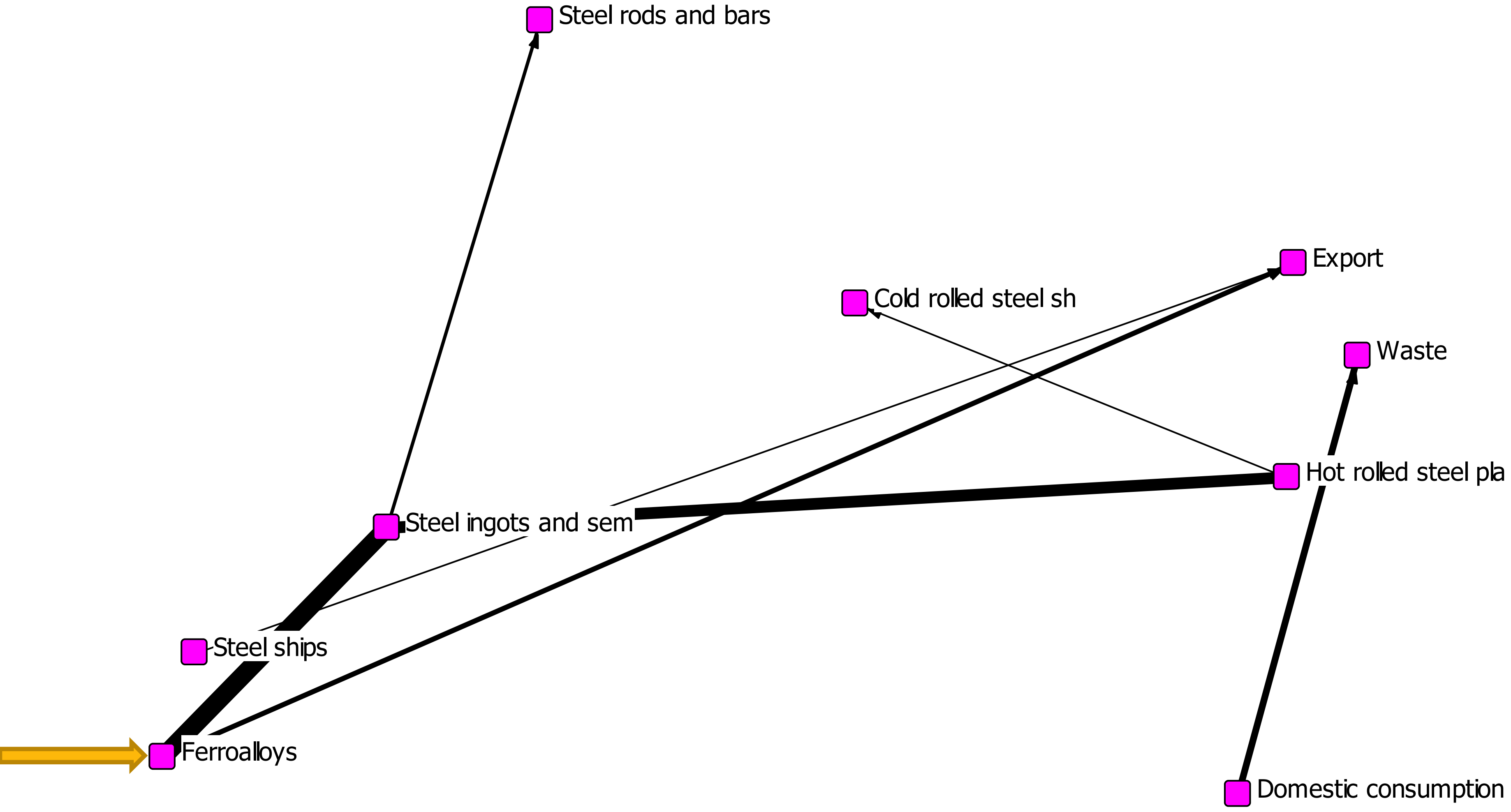
Lead 50% of the total flow (2007)



Manganese 80% of the total flow (2007)

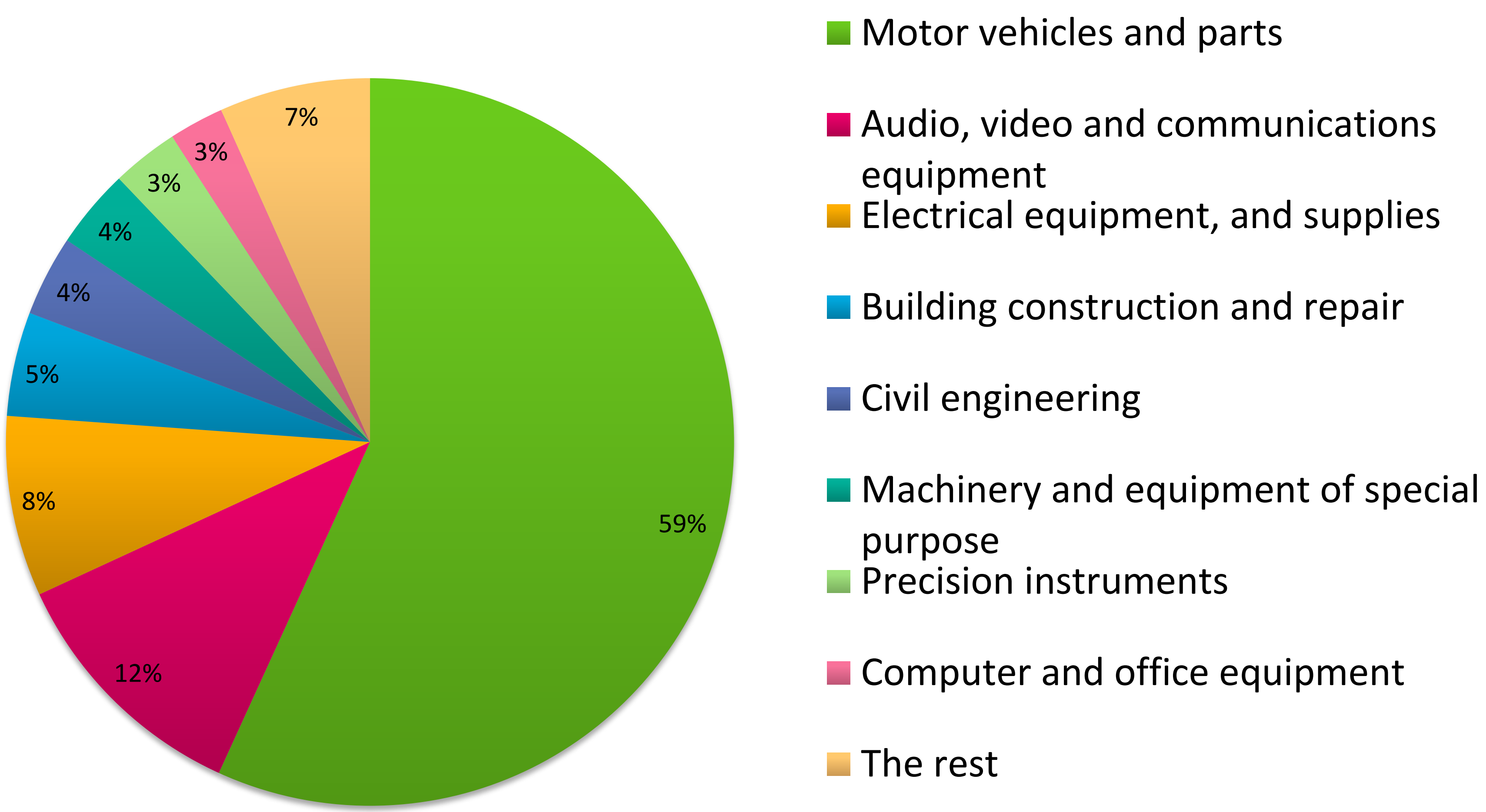


Manganese 50% of the total flow (2007)

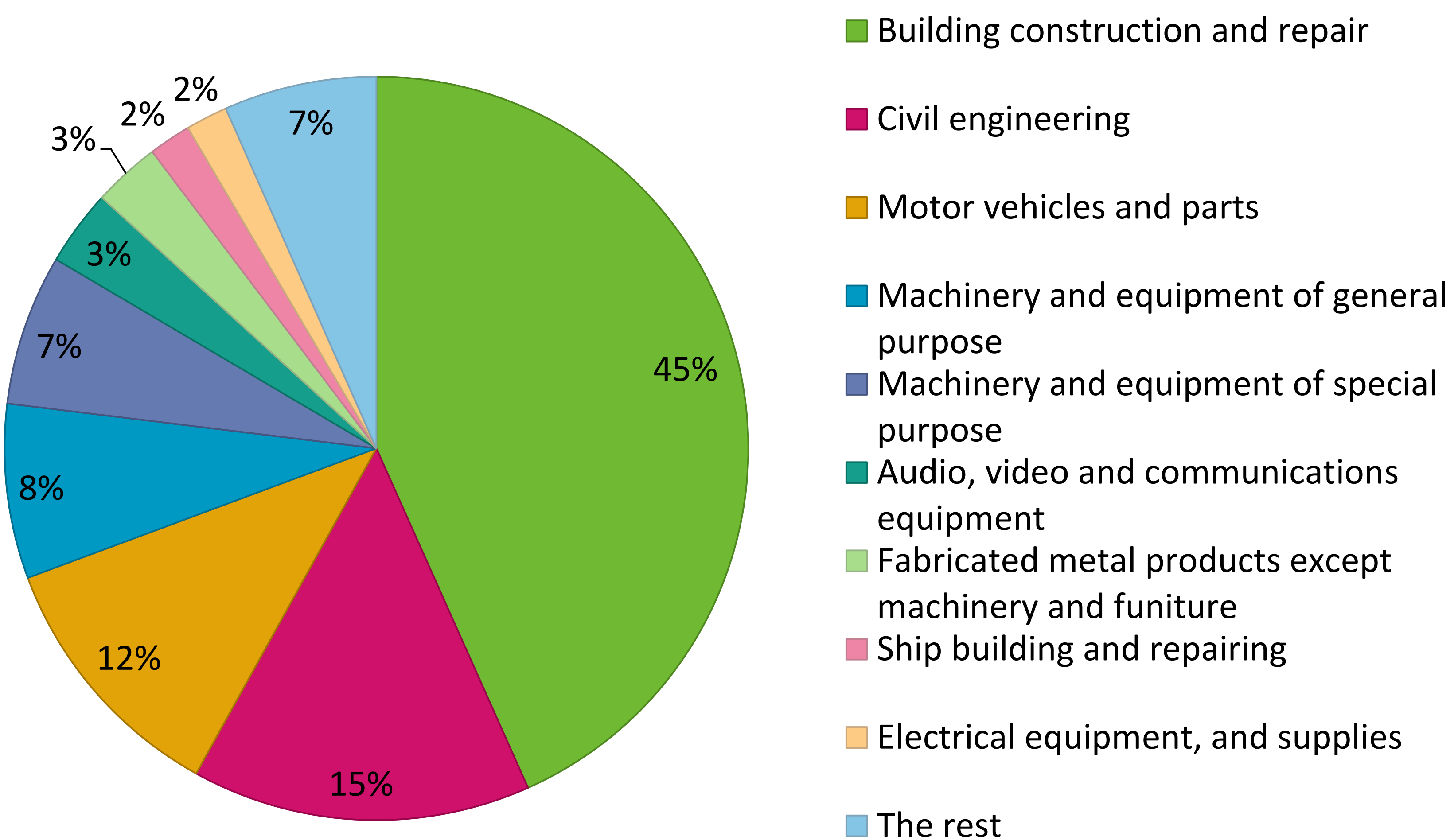


Cumulative results (1995 – 2007)

Composition of urban Pb stock



Composition of urban Al stock (c.a. 2008)



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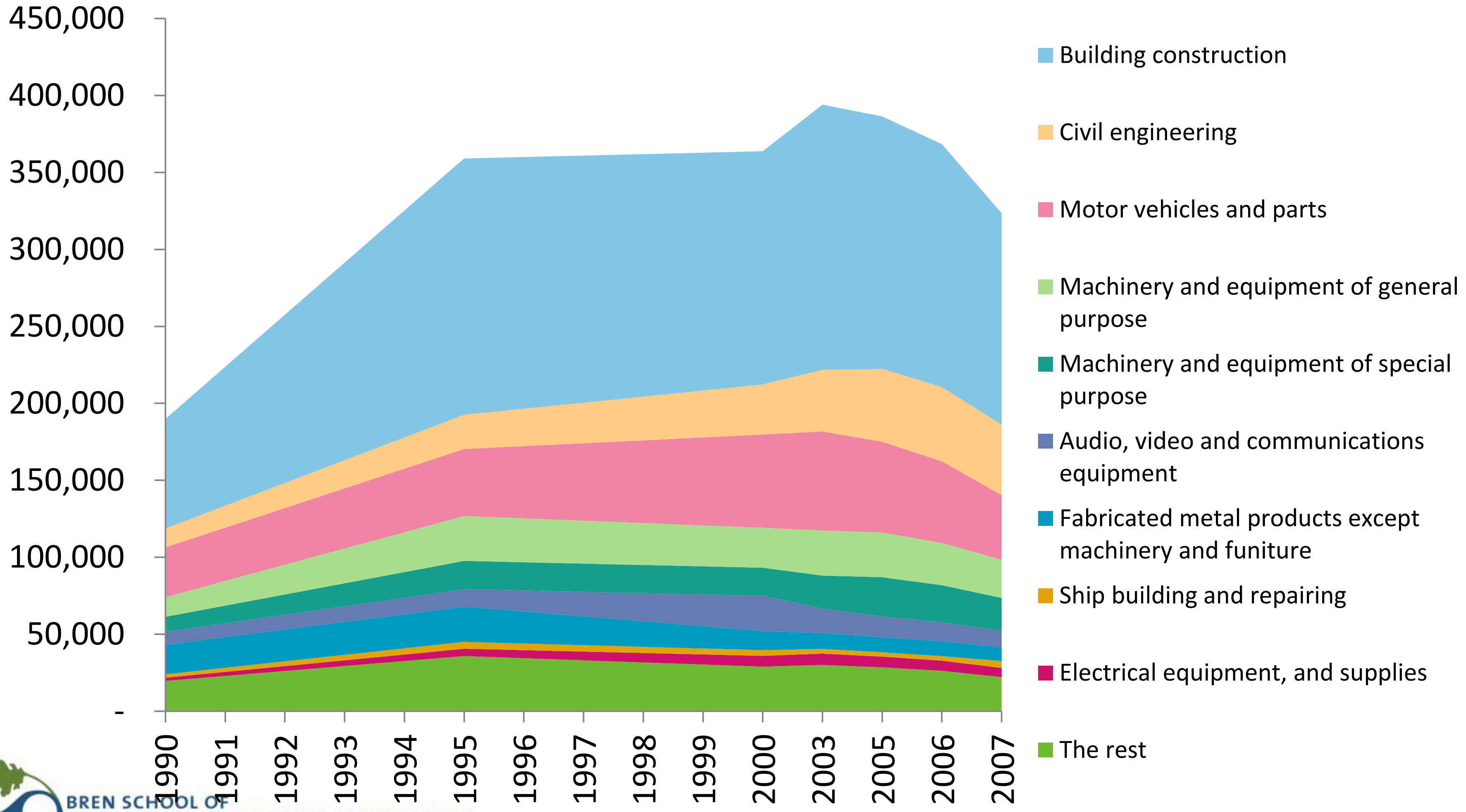
Aluminum stock trend



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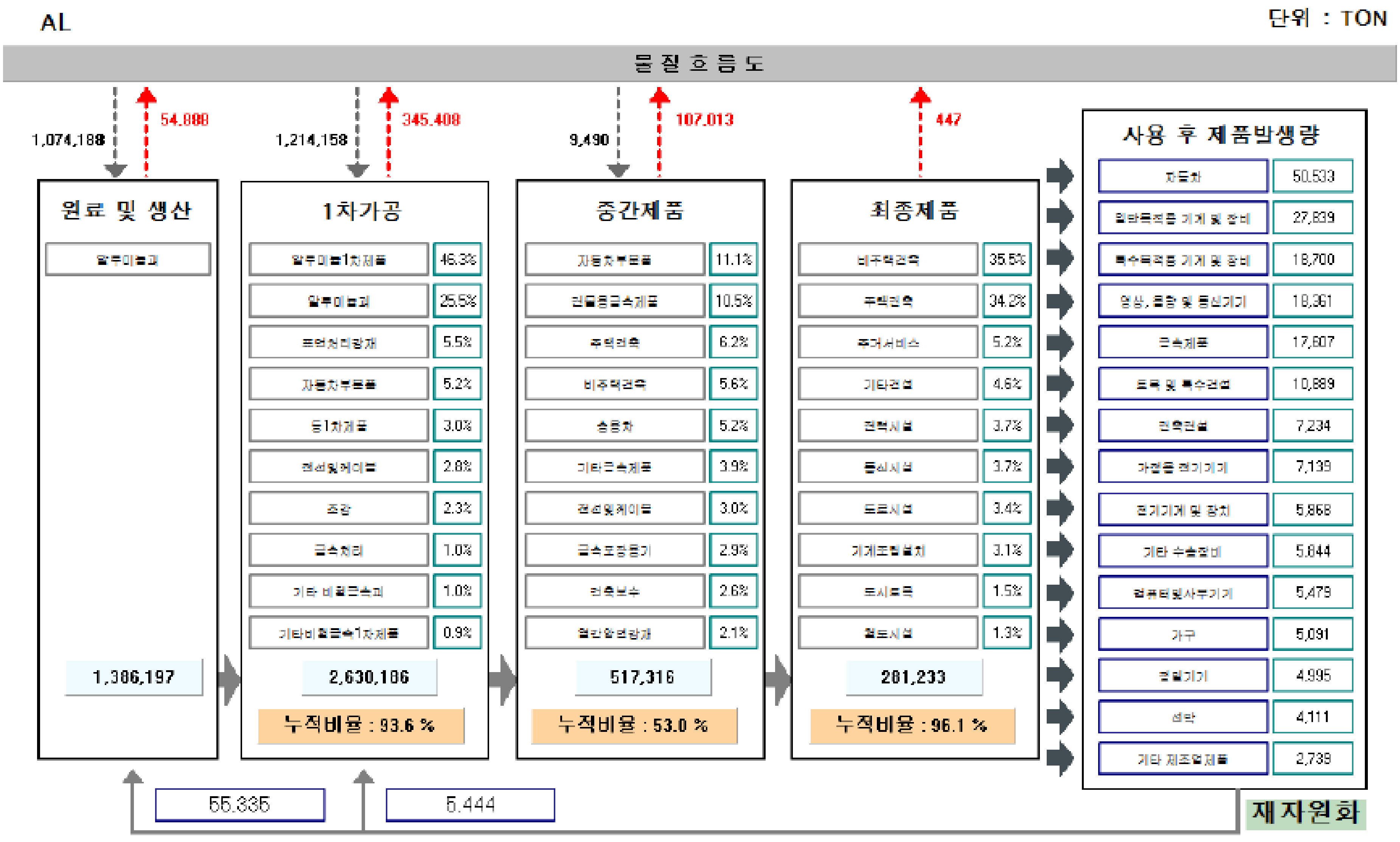
Software tool development



Verification

- Point data on material flows from South Korean National Institute of Geology and Resources, International Trade Association and various on-site survey.
- Material composition data from

鉱物資源マテリアルフロー

2008

平成21年8月

独立行政法人 石油天然ガス･金属鉱物資源機構

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Statistical inference (samples)

- Carried out for 15 data points
- Ex) the amounts of Al in “Primary Aluminum Products”; Pb in “Motor vehicle”

	Min	Standard Deviation	Maximum	Model results
Al	714,800	53,092	861,965	758,323
Pb	15,254	170	15,639	15,447

- Within 95% confidence interval
- (Almost too good)

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Summary and conclusions

- Modified supply-driven model provides useful information on material flows (not embodied material inputs).
- A case study carried out for 5 metals in South Korea showed remarkable reproducibility.
- Application of the model for bulk metals is expected to provide reasonable estimates.
- Application to rare metals would be more difficult.

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Summary and conclusions

- Motor vehicles, buildings, electronics, civil engineering infrastructure, and machinery are the major sources of metal stock.
- Materials are often finely distributed along the supply-chain and then often re-aggregated before arriving at the absorbing states.
- Small number of key industry nodes are important conduits of metal stocks and flows.

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Discussion

- Supply-driven model works well for *ex-post* analysis of physical stocks and flows.
- Absorbing Markov chain v.s. physical supply-driven model.
- Theories outside the IO literature may provide useful insights for the questions in IO frameworks and vise versa.

Thank you!

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