ENV-501 Material and Energy Flow Analysis

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Name: _____________________

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Intermediate Exam
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Duration 8:15 to 10:15

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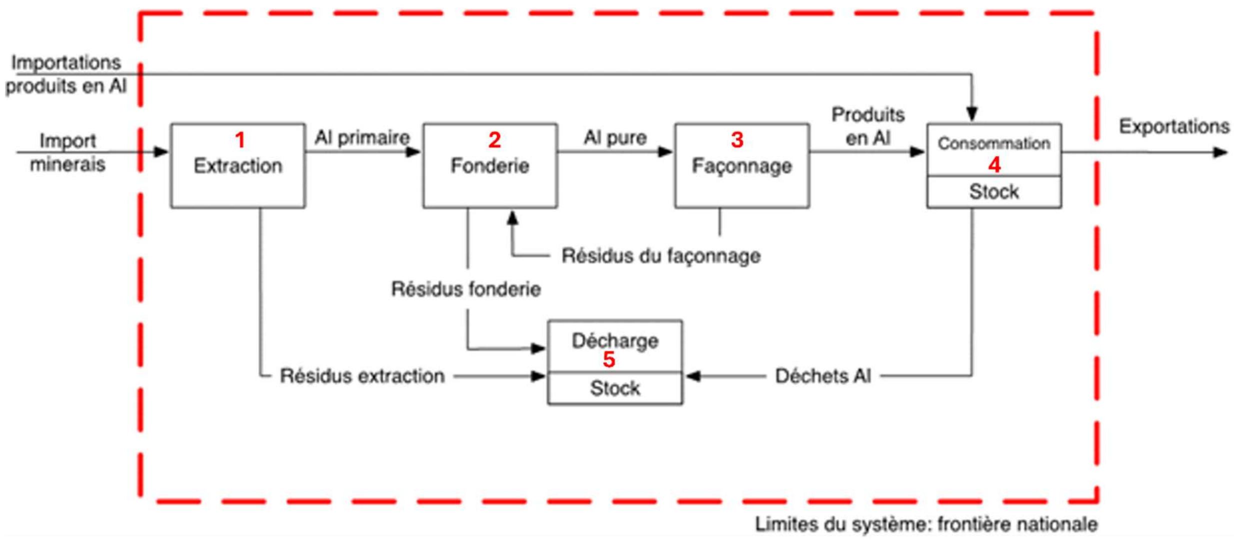
Part 1: Material Flow Analysis (30 points)

Following new regulations, Switzerland is seeking to assess the benefits of having aluminum recycling facilities on its territory, to meet its internal demand. To assess the benefits of recycling, you start from an initial scenario with no recycling of used aluminum within the limits of your system. Used aluminum from consumption is exported, representing 67% of the Export flow. A flow model of the aluminum production/consumption chain is proposed below (Figure 1).

Figure 1: Aluminum (Al) flow model



		Turnover	Stock growth	Stock
		kg/hab/an	kg/hab/an	kg/hab
Import minerais	Import minerals	16.5		
Al primaire	Al primary	16		
Al pure	Al pur	23		
Produits en Al	Al products	15		
Exportations	Exports	12		
Résidus extraction	Extraction residues	0.5		
Résidus fonderie	Foundry residues	1		
Résidus du façonnage	Shaping residues	8		
Déchets Al	Al waste	2		
Consommation	Consumption		+ 16	800
Décharge	Landfill		80	+ 3.5

Questions

1. Describe mathematically the system illustrated in Figure 1, i.e. the system equations for the stocks and the equations for the flows (do not solve). List the chosen parameters and describe them briefly **(8 points).**

   $I = \Delta S + O$ *for each stock:*

$$I_1 = F_{12} + F_{15} \qquad (1)$$

$$F_{12} + F_{32} = F_{23} + F_{25} \qquad (2)$$

$$F_{23} = F_{32} + F_{34} \qquad (3)$$

$$I_2 + F_{34} = \Delta S_4 + F_{45} + E \qquad (4)$$

$$F_{15} + F_{25} + F_{45} = \Delta S_5 \qquad (5)$$

2. Implement an internal recycling loop by introducing a recycled used aluminum flow from the consumption process into the foundry process.

   a) Describe mathematically the equation for the new consumption stock **(2 points).**

   We denote by F' the quantities that may differ from the initial ones due to the introduction of a recycling loop.

   Adding a recycling flow F_{42}*:*

$$I'_2 + F'_{34} = \Delta S_4 + F_{42} + F'_{45} + E' \qquad (6)$$

   b) Describe mathematically the transfer coefficient of the recycled used aluminum flow. In addition, describe mathematically the relationship between this transfer coefficient and the export **(5 points).**

   Transfer coefficient of the recycled used aluminium flow (which is not the recycling rate!!):

$$K_{42} = F_{42} / (I'_2 + F'_{34}) \qquad (7)$$

   Relationship with the export: we denote by U the used aluminium flow, representing 67% of the initial export flow:

$$U = 0.67 \cdot E$$

   Let r be the recycling rate of the used aluminium:

$$F_{42} = r \cdot U = r \cdot 0.67 \cdot E$$

$$\rightarrow K_{42} = \frac{r \cdot 0.67 \cdot E}{I_2' + F_{34}'}$$

c) Describe the relationship between the transfer coefficient of the recycled used aluminum flow and the mineral import input flow in the case where consumption remains constant. What is the percentage reduction in imports with a recycling rate of 87% **(6 points)?**

$$\textit{Recycled flow: } F_{42} = r \cdot 0.67 \cdot E = 0.87 \cdot 0.67 \cdot 12 = 6.99$$

Consumption remains constant → the foundry still needs to produce the same output ($F_{23}' = F_{23}$). *No accumulation in the foundry → input to foundry remains constant → the recycled flow is used to replace primary Al* (F_{12}):

$$➔ \ F'_{12} = F_{12} - F_{42} = 9.01$$

The transfer coefficient K_{12} *remains constant (it is a property of the process):*

$$➔ \ K_{12} = \frac{F_{12}}{I_1} = \frac{F_{12}'}{I_1'}$$

$$➔ \ I_1' = \frac{F'_{12} I_1}{F_{12}} = 9.29$$

In percents:

$$(I_1 - I'_1) \ / \ I_1 = \mathbf{43.7\%}$$

If only does the numerical application at the end:

$$I_1' = (F_{12} - r \cdot 0.67 \cdot E)\frac{I_1}{F_{12}} = 9.287$$

$$\textit{with a decrease of } (I_1 - I'_1) \ / \ I_1 = (16.5 - 9.287) \ / \ 16.5 = 43.7\%$$

3. The recycling rate will gradually increase to 95%. How would you account for its evolution over time? Propose a simplified equation to do so **(9 points).**

Recycling rate is gradually increasing to 95%, so the focus should be on the evolution of the recycling rate r over a period of time.We could assume that the recycling rate starts at 87% (r = 0.87) and increases to 95% (0.95) over a given time, which could be modeled as a function of time *t*

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Assuming a linear increase of recycling rate over a period of time:

The recycling rate as a function of time equals the intial recycling rate, plus the increment of the recycling rate per unit of time, multiplied by the intermediate time period (or elapsed time)

$$r(t) = r_{,start} + [(r_{,end} - r_{,start})/T] * t$$

- $r(t)$ = variation of recycling rate over time
- r, start = initial recycling rate at $t = 0$ (in this case 87%)
- r, end = final recycling rate at $t = T$ (in this case 95%)
- $[(r_{,end} - r_{,start})/T]$ = Increment of the recycling rate per total time (or the rate of increase in recycling per unit of time)
- T = Total time period to reach the final recycling rate
- t = intermediate time period (or elapsed time) (can vary from 0 to T)

Part 2: Spatial Material Flow Analysis (10 points)

Spatial analysis of material flows and stocks can greatly improve resource management, in particular reuse and recycling. This part is inspired by the work of Tanikawa et al. 2014. Figure 2 below represents the lost material stock of buildings in Sanriku and Ishinomaki due to the Great East Japan Earthquake in 2011, in tons (TerraMetrics 2013; map Data SIO, NOAA, U.S. Navy, NGA, GEBCO, and Cnes/Spot Image 2013). Buildings on the east coast of Japan included wooden houses, up to three story building structures made of steel and reinforced concrete buildings.

Based on the results shown in Figure 2, briefly explain how you would split the lost material stock between wood, steel and aggregates **(7 points)**. State one advantage and one disadvantage of your approach **(3 points)**.

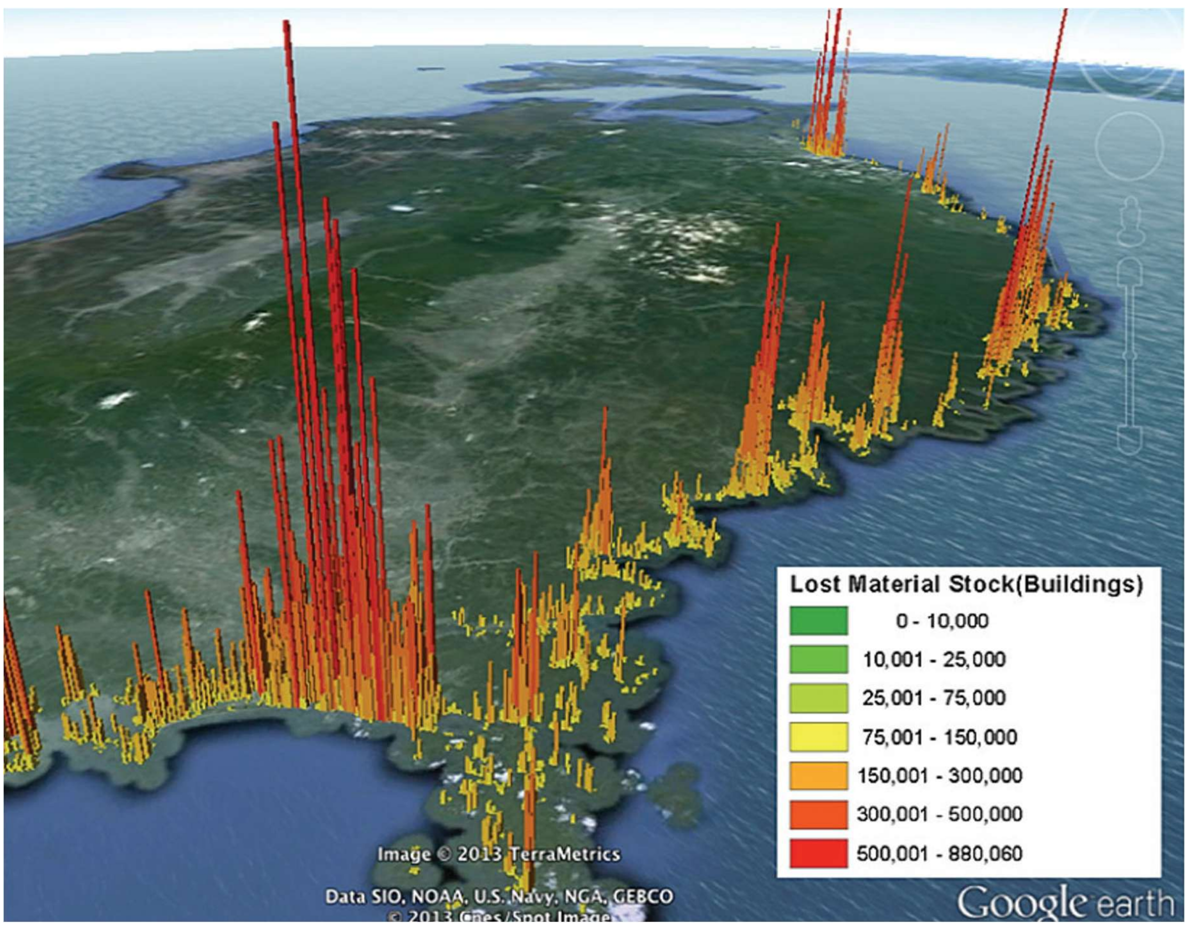
Broadly:

*Identify buildings impacted, and at what degree (e.g. through disaster reports, images)
*Classification of building by main material (e.g., wood, steel, aggregate)
*Estimate building area/volume
*Apply material intensities per building area/volume
*Summarize all materials by building (bottom-up)

Advantages: e.g. generalization gives quick results
Disadvantages: e.g. due to generalization, precise results on material stocks data may be lacking

2 points: Only classifying by the color of the graph (at least some classification of materials).
3 points: Assuming city areas have more concrete and rural areas have more wood (at least a certain level of classification of materials, by clustering and other broad assumptions).
4 points: Clustering and also assigning certain material intensities, classifying by construction period, etc.
5 points: Clustering and also assigning certain material intensities, classifying by construction period, building archetypes, but lacks further description of steps.
6 points: More complete description of steps but misses a bit on the steps for estimation.
7 points: Identification of impacted buildings, classification by the main material, material intensities, summarizing the materials, and arriving at a final result. Overall, a more straightforward procedure.

Figure 2: Lost material stock of buildings in Sanriku and Ishinomaki (tons)



Part 3: Input Output Analysis (20 points)

Financial services represent an important part of economic activities in Switzerland. In monetary terms, approximately 5% of gross domestic product is the result of financial activities, excluding but equivalent to insurances. The environmental impact of such activities in Switzerland remains small, but much of the funding remains dedicated to extractive industries, fossil fuels, metallic and non-metallic minerals. This is much talked about, thanks to citizens and associations holding private banks as well as the national bank accountable. The value added of financial services means jobs in the sector are well paid, and much of these high wages are spent on luxury cars and air travel. In fact, recent research has shown that if the impact generated by employees and their lifestyles were factored in the impact of each economic activity, banking would be just as damaging as extractive industries.

Your task is to estimate the impact of fossil fuel consumption and emissions from transportation associated with financial activities. The direct consumption of fuels corresponds to approximately 250'000 and 6 million tons of CO_2 emissions per year as a result of financial and transport activities, respectively. Households, which represent the largest share of final consumption, spend approximately 8 billion swiss francs (CHF) on financial services and 9.4 billion in transportation.

A quick look at economic input output data allows you to establish the links between both activities, financial services and transportation, summarized in the table below, in million CHF.

	Financial services	Transport	Output
Financial services	16'300	600	70'000
Transport	110	420	30'000

When Matrix $A = \begin{bmatrix} a & b \\ c & d \end{bmatrix}$

$$A^{-1} = \frac{1}{ad - bc} \begin{bmatrix} d & -b \\ -c & a \end{bmatrix}$$

Questions

1. Considering the interactions between both financial services and transport, estimate the CO_2 emissions from the transport sector induced by the final consumption of financial services from Swiss households **(12 points)**

   This is a classical exercise of input-output analysis, for which you can always follow the same procedure.

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i. *Identify matrix of transactions Z (in mioCHF), the total output vector X (in mioCHF), the emissions vector F (in tons) and the household demand vector of financial services Y_{H_FIN} (in mioCHF):*

$$Z = \begin{pmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{pmatrix} = \begin{pmatrix} 16'300 & 600 \\ 110 & 420 \end{pmatrix}$$

$$X = \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} = \begin{pmatrix} 70'000 \\ 30'000 \end{pmatrix}$$

$$F = \begin{pmatrix} 250'000 \\ 6'000'000 \end{pmatrix} \textit{ in tons}$$

$$Y_{H\_FIN} = \begin{pmatrix} 8'000 \\ 0 \end{pmatrix}$$

ii. *Compute the matrix of transaction coefficients A (in mioCH/mioCHF, i.e. no units) and the vector of emission coefficients (in tons/mioCHF):*

$$a_{ij} = z_{ij}/x_j$$

$$f_i = F_i/x_i$$

// (in matrix form: $A = Z\,\hat{X}^{-1}$, with $\hat{X} = \begin{pmatrix} x_1 & 0 \\ 0 & x_2 \end{pmatrix}$)

$$A = \begin{pmatrix} z_{11}/x_1 & z_{12}/x_2 \\ z_{21}/x_1 & z_{22}/x_2 \end{pmatrix} = \begin{pmatrix} 16300/70000 & 600/30000 \\ 110/70000 & 420/30000 \end{pmatrix} \approx \begin{pmatrix} 0.233 & 0.020 \\ 0.002 & 0.014 \end{pmatrix}$$

$$f = \begin{pmatrix} F_1/x_1 \\ F_2/x_2 \end{pmatrix} = \begin{pmatrix} 250'000/70'000 \\ 6'000'000/30'000 \end{pmatrix} = \begin{pmatrix} 3.571 \\ 200'000 \end{pmatrix} \textit{ in tons per mio CHF}$$

iii. *Compute the Leontief inverse:*

$$L = (I - A)^{-1} \approx \begin{pmatrix} 1.304 & 0.026 \\ 0.002 & 1.014 \end{pmatrix} \textit{ // using the formula for inversion given in the exam}$$

Reminder: L relates any final demand vector Y' to the required output X' to meet this final demand, taking into account the internal exchanges between economic activities. This is expressed by the formula X' = LY', with $L = (I - A)^{-1}$ derived from $X' = AX' + Y'$. Note that X' is not necessarily equal to the initial output vector X that we used to compute the matrix of transaction coefficients A. A is a property of the economic system, and once computed, we can use it for many X' and Y' values.

iv. *Compute the output from the transport sector required by the final consumption of financial services from Swiss households:*

$$X_{H\_FIN} = LY_{H\_FIN} = \begin{pmatrix} 1.304 & 0.026 \\ 0.002 & 1.014 \end{pmatrix} \begin{pmatrix} 8'000 \\ 0 \end{pmatrix} = \begin{pmatrix} 10'432 \\ \mathbf{16} \end{pmatrix}$$

➔ *The demand of financial services by households (8000 mio) requires* $x_{H\_FIN,2} = 16$ *mioCHF of output by the transportation sector (note that the computation of* $x_{H\_FIN,1}$ *was not necessary here, since we are only interested in the output of the transport sector).*

v. *Compute the* CO_2 *emissions from the transport sector induced by the final consumption of financial services from Swiss households:*

➔ ***CO_2 emissions from the transport sector induced by the final consumption of financial services from Swiss households:*** *we simply multiply by the direct emissions coefficient of transport activities,* f_2

$$CO2\_emissions_{H\_FIN \rightarrow TRANS} = f_2 \cdot x_{H\_FIN,2} = 200'000 \cdot 16 = 3'200'000 \textit{ tons}$$

2. Are your results over- or underestimating the actual emissions? Briefly explain why and how you would improve your estimate **(8 points)**

If by "actual emissions" we mean total emissions induced by the consumption of financial services, it is an underestimation because:

- It neglects the direct emissions of financial services
- It neglects the indirect emissions of all other economic sectors except transport (for example: electricity consumption)

➔ Improvements:
- Include direct emissions of financial services
- Include other sectors (like electricity)

Answer sheet

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Answer sheet

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Answer sheet

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