Circular economy innovations in a 2-area input-output stock-flow consistent dynamic model

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European Commission Grant, Project 101003491: "A Just Transition to the Circular Economy" (JUST2CE)

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- Two main milestones / deliverables linked with WP5:
  - a systematic review of current literature on macroeconomic models for assessing the transition towards a CE
  - a formal model (or set of models) to simulate and compare alternative CE policies and transition scenarios

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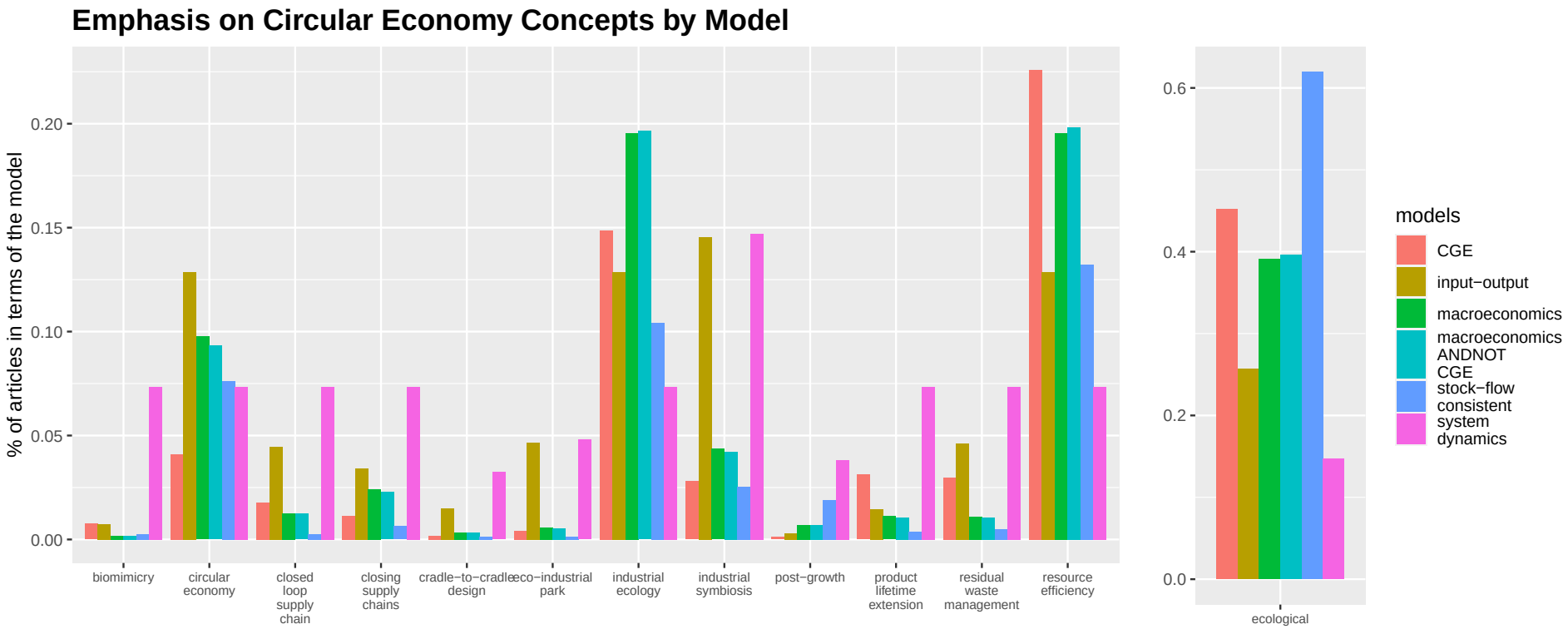
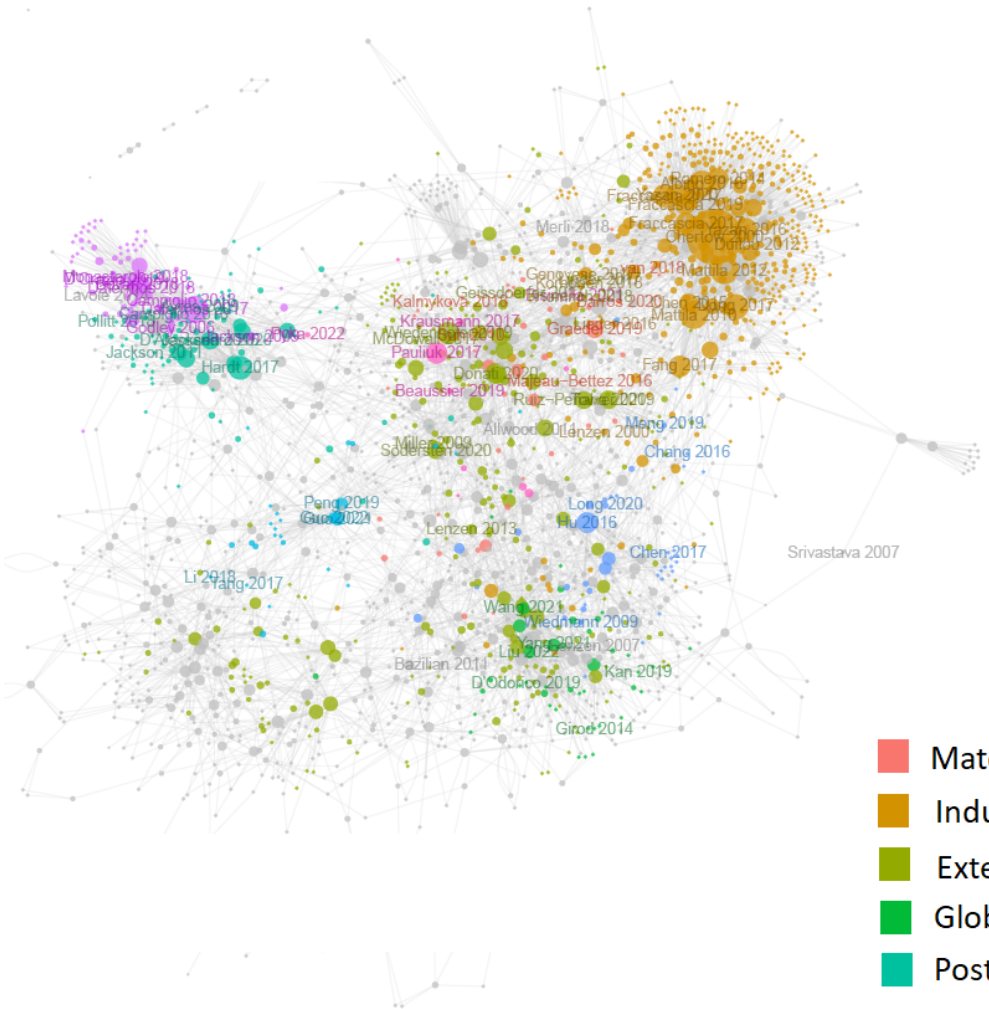
- We have focused on both topics and modeling techniques
- We have identified, discussed, and assessed the most popular/promising tools (to model the transition...)

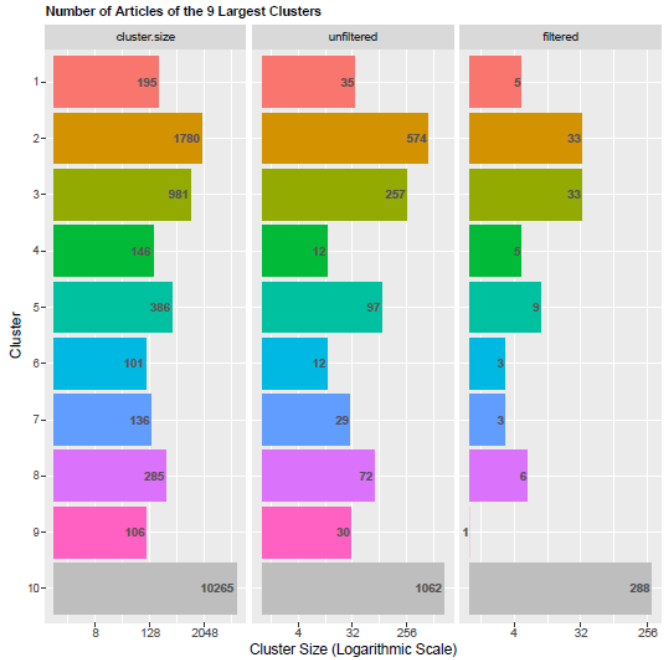
Figure A1. Concepts and models



Source: Valles-Codina et al. (2022)

Figure A2. Citation network of filtered entries





- Material flow analysis
- Industrial symbiosis
- Extended IO
- Global value chain
- Post-growth SFC
- CGE (electric vehicles)
- Carbon footprint analysis
- Post-Keynesian SFC
- IAMs

Source: elaboration on Valles-Codina et al. (2022)

The model: basic features

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- In principle, we can disaggregate SFC models by crossbreeding them with IO models... (Hardt and O'Neill 2017)

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- Two-fold aim:
  1) To bridge the gap by developing a benchmark 2A-IO-SFC model (and related codes)
  2) To assess the impact of a simple CE innovation on the economy, the society and the ecosystem

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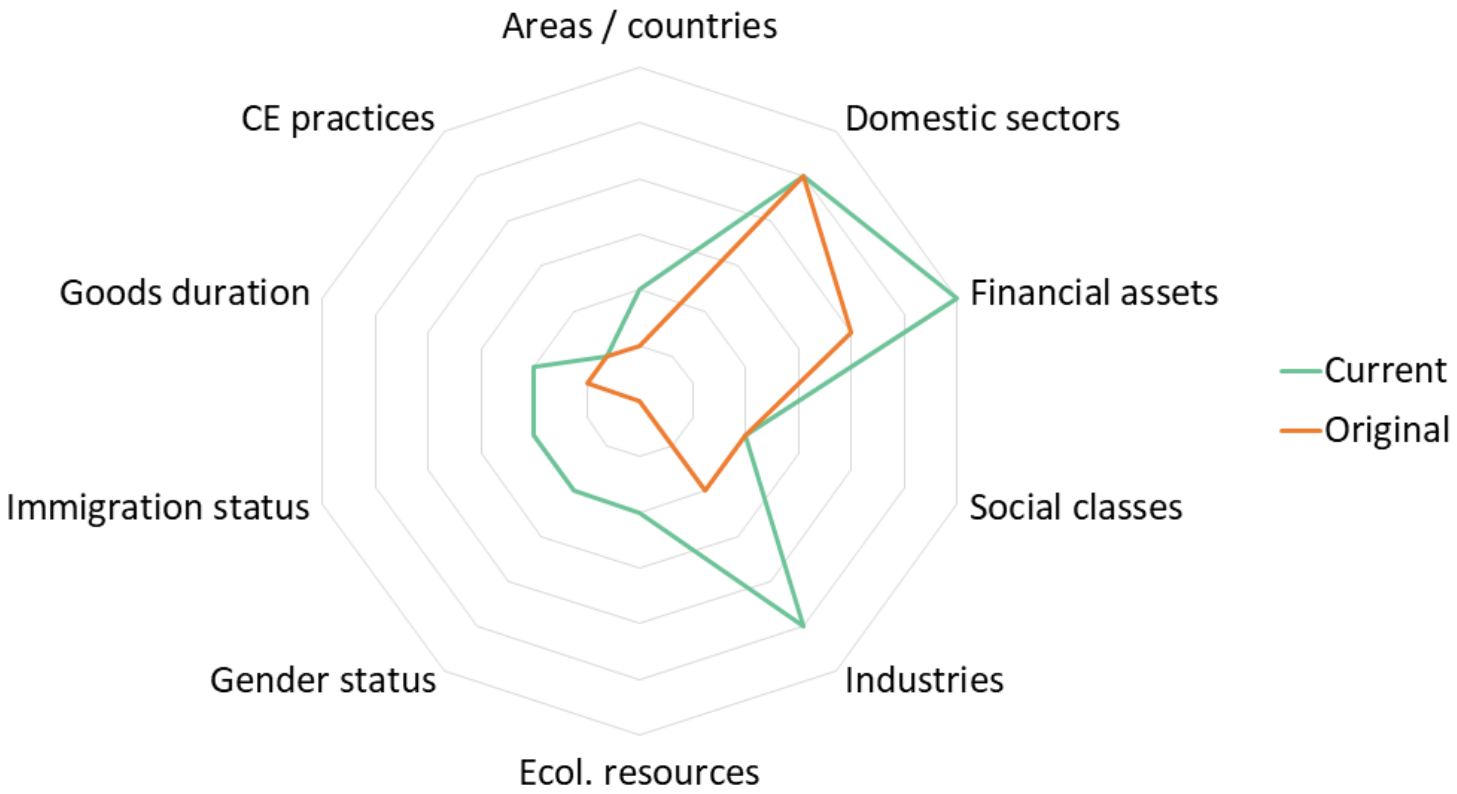
d) Solution: numerical simulations (*R* code), 100 periods, 100 iterations

Figure 1. Model dimensions



Assets and liabilities

Table 1: Balance-sheet matrix in period 20 (curr. p., Area 1 currency)

	Area 1						Area 2					
	H	F	G	B	CB	*xr*	H	F	G	B	CB	Tot
Money	74.31				-74.31	1	74.31				-74.31	0.00
Advances				0.00	0.00	1				0.00	0.00	0.00
Deposits	444.09			-444.09		1	444.09			-444.09		0.00
Loans	-14.66	-95.86		110.53		1	-14.66	-95.86		110.53		0.00
Area 1 bills	27.86		-449.66	333.56	74.31	1	13.93					0.00
Area 2 bills	13.93				0.00	1	27.86		-449.66	333.56	74.31	0.00
Area 1 shares	11.14	-11.70				1	0.56					0.00
Area 2 shares	0.56					1	11.14	-11.70				0.00
Capital stock		107.56				1		107.56				215.13
Net financial wealth	-557.22		449.66			1	-557.22		449.66			-215.13
Total	0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00

Transactions and Δ in stocks

Table 2: Transactions-flow matrix in period 20 (curr. p., Area 1 currency)

	Area 1							Area 2						
	H	F (y)	F (k)	G	B	CB	*xr*	H	F (y)	F (k)	G	B	CB	Tot
Consumption	-745.07	745.07					1	-745.07	745.07					0.00
Investment		8.04	-8.04				1		8.04	-8.04				0.00
Government spending		183.87		-183.87			1		183.87		-183.87			0.00
Export of Area 1		28.78					1		-28.78					0.00
Import of Area 1		-28.78					1		28.78					0.00
[Value added]		[922.09]					1		[922.09]					0.00
Wage bill	432.49	-432.49					1	432.49	-432.49					0.00
Corporate profit	480.64	-480.64	0.00				1	480.64	-480.64	0.00				0.00
Amortization		-5.24	5.24				1		-5.24	5.24				0.00
Bank profit	8.83				-8.83		1	8.83				-8.83		0.00
CB profit				2.96		-2.96	1				2.96		-2.96	0.00
Income tax revenue	-184.73			184.73			1	-184.73			184.73			0.00
VAT revenue		-14.61		14.61			1		-14.61		14.61			0.00
Tariffs revenue		-0.28		0.28			1		-0.28		0.28			0.00
Interests on deposits	8.83				-8.83		1	8.83				-8.83		0.00
Interests on loans	-0.55	-3.72			4.27		1	-0.55	-3.72			4.27		0.00
Interests on Area 1 bills	1.11			-18.01	13.39	2.96	1	0.56						0.00
Interests on Area 2 bills	0.56					0.00	1	1.11			-18.01	13.39	2.96	0.00
Change in money stock	-0.29					0.29	1	-0.29					0.29	0.00
Change in advances					0.00	0.00	1					0.00	0.00	0.00
Change in deposits	-2.52				2.52		1	-2.52				2.52		0.00
Change in loans	0.90		2.76		-3.66		1			2.76		-3.66		0.00
Change in Area 1 bills	-0.11			-0.70	1.14	-0.29	1	-0.05						0.00
Change in Area 2 bills	-0.05					0.00	1	-0.11			-0.70	1.14	-0.29	0.00
Change in Area 1 shares	-0.04		0.04				1							0.00
Change in Area 2 shares							1	-0.04		0.04				0.00
Revaluation effects	0.00	0.00	0.00	0.00	0.00	0.00	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00

Cross-industry interdependencies

Table 3: Baseline: input-output matrix in period 20 (curr. p., Area 1 currency)

	Area 1 demand for inputs					Area 2 demand for inputs						
	M	A	S	W	R	M	A	S	W	R	Final dem.	Output
Area 1 production												
Manufacturing	67.01	66.89	67.13	26.13	0.00	5.58	5.57	5.59	2.18	0.00	312.33	558.43
Agriculture	67.01	66.89	67.13	26.13	0.00	5.58	5.57	5.59	2.18	0.00	311.35	557.45
Services	67.01	66.89	67.13	26.13	0.00	5.58	5.57	5.59	2.18	0.00	313.31	559.41
Waste manag.	67.00	66.89	67.12	0.00	0.00	5.58	5.57	5.59	0.00	0.00	0.00	217.76
Recycling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Area 2 production												
Manufacturing	5.58	5.57	5.59	2.18	0.00	67.01	66.89	67.13	26.13	0.00	312.33	558.43
Agriculture	5.58	5.57	5.59	2.18	0.00	67.01	66.89	67.13	26.13	0.00	311.35	557.45
Services	5.58	5.57	5.59	2.18	0.00	67.01	66.89	67.13	26.13	0.00	313.31	559.41
Waste manag.	5.58	5.57	5.59	0.00	0.00	67.00	66.89	67.12	0.00	0.00	0.00	217.76
Recycling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Value added												
~ Compensation of employees	128.65	128.41	128.89	46.55	0.00	128.65	128.41	128.89	46.55	0.00		
~ G.O. surplus and mixed incomes	139.41	139.18	139.64	86.27	0.00	139.41	139.18	139.64	86.27	0.00		
Taxes on production	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
Output	558.43	557.45	559.41	217.76	0.00	558.43	557.45	559.41	217.76	0.00		

Area-specific physical flows

Table 4: Physical flow matrix in period 20 (matter = Gt, energy = EJ)

	A1 matter	A2 matter	Global matter	A1 energy	A2 energy	Global energy
Inputs						
Extracted matter	1449.82	1449.82	2899.65			
Recycled matter	22.62	22.62	45.24			
Renewable energy				1505.43	1505.43	3010.86
Non-renewable energy	19.87	19.87	39.73	9247.65	9247.65	18495.29
Oxygen	53.05	53.05	106.09			
Outputs						
Industrial CO_2 emissions	-72.91	-72.91	-145.83			
Discarded stock	-113.09	-113.09	-226.19			
Dissipated energy				-10753.08	-10753.08	-21506.16
Δ in socio-economic stock	1359.35	1359.35	2718.7			
Difference	0	0	0	0	0	0

Global physical stocks and related changes

Table 5: Physical stock-flow matrix in period 20 (matter = Gt, energy = EJ)

	Material reserves	Energy reserves	CO_2 concentration	Socio-economic stock
Initial stock	9451266.99	-201040.39	2101.05	40831.85
Resources converted into reserves	193156.73	1536.04		
CO_2 emissions			145.83	
Production of material goods				2944.88
Extraction/use of matter/energy	-2899.65	-18495.29		
Distruction of socio-ec. stock				-226.19
Final stock	9641524.08	-217999.64	2246.87	43550.54
Difference	0	0	0	0

Selected equations: households

- Total "real" consumption in each area is:

$$c^z = \alpha_1^z \cdot \frac{YD_w^z}{E(p_A^z)} + \alpha_2^z \cdot \frac{YD_c^z}{E(p_A^z)} + \alpha_3^z \cdot \frac{V_{-1}^z}{p_{A,-1}^z} \tag{1}$$

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- Households' total disposable income in each area is:

$$\begin{aligned} YD^z = {} & WB^z + DIV^z + FB^z + \\ & + r_{m,-1}^z \cdot M_{h,-1}^z + r_{b,-1}^z \cdot B_{s,z,-1}^z + xr_{-1}^f \cdot r_{b,-1}^f \cdot B_{s,z,-1}^f + \\ & + \Delta xr^f \cdot (B_{s,z,-1}^f + E_{s,z,-1}^f) - r_{h,-1}^z \cdot L_{h,-1}^z - T^z \end{aligned} \tag{2}$$

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- Households' net wealth is:

$$V^z = V_{-1}^z + YD^z - c^z \cdot p_A^z \tag{3}$$

Selected equations: firms (current)

- Let us consider a 10×10 global production. The final demand vector of Area 1 is:

$$\mathbf{d}^z = \begin{pmatrix} \beta_1^z \\ \vdots \\ \beta_{10}^z \end{pmatrix} \cdot c^z + \begin{pmatrix} \iota_1^z \\ \vdots \\ \iota_{10}^z \end{pmatrix} \cdot i_d^z + \begin{pmatrix} \sigma_1^z \\ \vdots \\ \sigma_{10}^z \end{pmatrix} \cdot gov^z + \begin{pmatrix} \eta_{1,z}^f \\ \vdots \\ \eta_{10,z}^f \end{pmatrix} \cdot exp^z - \begin{pmatrix} \eta_1^z \\ \vdots \\ \eta_{10}^z \end{pmatrix} \cdot imp^z \quad (4)$$

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- The gross output vector is:

$$\mathbf{x}^z = \mathbf{A} \cdot \mathbf{x}^z + \mathbf{d}^z = (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{d}^z, \ with : \mathbf{A} = \begin{pmatrix} a_{1,1} & \cdots & a_{1,10} \\ \dots & \ddots & \dots \\ a_{10,1} & \cdots & a_{10,10} \end{pmatrix} \quad (5)$$

Selected equations: firms (current)

- Let us consider a 10×10 global production. The final demand vector of Area 1 is:

$$\mathbf{d}^z = \begin{pmatrix} \beta_1^z \\ \vdots \\ \beta_{10}^z \end{pmatrix} \cdot c^z + \begin{pmatrix} \iota_1^z \\ \vdots \\ \iota_{10}^z \end{pmatrix} \cdot i_d^z + \begin{pmatrix} \sigma_1^z \\ \vdots \\ \sigma_{10}^z \end{pmatrix} \cdot gov^z + \begin{pmatrix} \eta_{1,z}^f \\ \vdots \\ \eta_{10,z}^f \end{pmatrix} \cdot exp^z - \begin{pmatrix} \eta_1^z \\ \vdots \\ \eta_{10}^z \end{pmatrix} \cdot imp^z \quad (4)$$

- The gross output vector is:

$$\mathbf{x}^z = \mathbf{A} \cdot \mathbf{x}^z + \mathbf{d}^z = (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{d}^z, \ with : \mathbf{A} = \begin{pmatrix} a_{1,1} & \cdots & a_{1,10} \\ \dots & \ddots & \dots \\ a_{10,1} & \cdots & a_{10,10} \end{pmatrix} \quad (5)$$

- The value added in each area is:

$$YN^z = c^z \cdot p_A^z + i_d^z \cdot p_I^z + gov^z \cdot p_G^z + EXP^z - IMP^z - VAT^z - TAR^z \quad (6)$$

Selected equations: consumer choices

- The share of manufacturing products to total consumption is stable:

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- The share of services to total consumption increases as disposable incomes (expressed in real terms, using the price of services) increase:

$$\beta_3^z = \beta_{3,-1}^z + \beta_{31}^z \cdot \frac{YD_{w,-1}^z}{p_{3,-1}^z} + \beta_{32}^z \cdot \frac{YD_{c,-1}^z}{p_{3,-1}^z} \tag{8}$$

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- The share of agricultural products is calculated residually, and tends to decline as the economy grows:

$$\beta_2^z = 1 - \beta_1^z - \beta_3^z \tag{9}$$

with $\beta_2^z \geq 0$.

Selected equations: firms (capital)

- The target stock of fixed capital depends on industry-specific target capital to output ratios:

$$k^{z*} = \mathbf{p}_{-1}^{zT} \cdot \left(\mathbf{h}^{z} \odot \mathbf{x}_{-1}^{z}\right) \cdot \frac{1}{p_{I,-1}^{z}} \tag{10}$$

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$$i_d^z = \gamma^z \cdot \left(k^{z*} - k_{-1}^z\right) + \delta^z \cdot k_{-1}^z \tag{11}$$

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- The end-of-period stock of bank loans is defined residually:

$$L_F^z = L_{F,-1}^z + i_d^z \cdot p_I^z - AF^z - FF_u^z - \Delta E_s^z \tag{12}$$

where:

$$AF^z = \delta^z \cdot k_{-1}^z \cdot p_I^z - k^z \cdot \Delta p_I^z$$

Selected equations: commercial banks

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$$M_s^z = M_h^z \tag{15}$$

Selected equations: labour market and popul.

- The total employment in each area is:

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$$\mathbf{IMM}^z = \gamma^z_{imm,0} \odot \mathbf{POP}^f_{-1} + \gamma^z_{imm,1} \odot \mathbf{un}^f_{-1} + \gamma^z_{imm,2} \odot (\mathbf{w}^z_{-1} - \mathbf{w}^f_{-1}) \tag{18}$$

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- In each industry, the percentage of female workers (gender segregation) is:

$$\rho^z_j = \rho^z_{0j} - \rho^z_{1j} \cdot (w^z_j - w^z_{j,-1}) \tag{19}$$

Selected equations: government and CB

- The government budget deficit in each area is:

$$DEF_g^z = gov^z \cdot p_G^z + r_{b,-1}^z \cdot B_{s,-1}^z - F_{cb}^z - T^z - VAT^z - TAR^z \tag{20}$$

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- Therefore, the supply of government bills is:

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- Cash supply adjusts to households' demand:

$$H_s^z = H_h^z \tag{23}$$

Selected equations: prices

- Firms use a mark-up rule. The unit price of production vector is:

$$\mathbf{p}^{z*} = \mathbf{w}^{z} \odot \mathbf{l}^{z} + \mathbf{p}^{z*} \cdot \mathbf{A} \odot \mathbf{m}^{z*} \odot \mathbf{h}_{d}^{z} \tag{24}$$

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- However, market prices also depend on labour-constrained potential output, vat and tariffs:

$$\mathbf{p}^{z} = \left[\mathbf{p}^{z*} + \Gamma_{x}^{z} \odot (\mathbf{x}_{-1}^{z} - \mathbf{x}_{-1}^{z*})\right] \odot \left[\begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix} + \tau_{vat}^{z} + \tau_{tar}^{f}\right] \tag{25}$$

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- The consumer price index or average price of consumption is:

$$p_{A}^{z} = \mathbf{p}^{z\mathcal{T}} \cdot \beta^{z} \tag{26}$$

Selected equations: portfolio choices

- Households' demand for domestic bills is:

$$\frac{B^z_{h,z}}{V^z} = \lambda_{10} + \lambda_{11} \cdot r^z_{b,-1} - \lambda_{12} \cdot \left(r^f_{b,-1} + \frac{\Delta x r^f}{x r^f} \right) - \lambda_{13} \cdot r^z_{m,-1} - \lambda_{14} \cdot \frac{YD^z}{V^z} + \\ - \lambda_{15} \cdot r^z_{e,-1} - \lambda_{16} \cdot \left(r^f_{e,-1} + \frac{\Delta x r^f}{x r^f} \right) \tag{27}$$

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- The redundant equation is:

$$B^z_{cb,z} = B^z_s - B^z_{s,z} - B^z_{s,f} - B^z_b$$

Selected equations: waste and emissions

- The quantity of waste generated in industry is:

$$wa_j^z = wa_{j,-1}^z + x_j^z \cdot \zeta_j^z - x_j^z \cdot a_{5,j} \tag{30}$$

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- Industrial CO_2 emissions generated in each industry are:

$$emis_j^z = x_j^z \cdot (1 - \eta_{en,j}^z) \cdot \varepsilon_j^z \cdot \beta_e^z \tag{31}$$

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- The total atmospheric CO_2 concentration is calculated using equations that approximate the carbon cycle.

Figure 2. Sankey diagram of transactions (in $t = 20$)

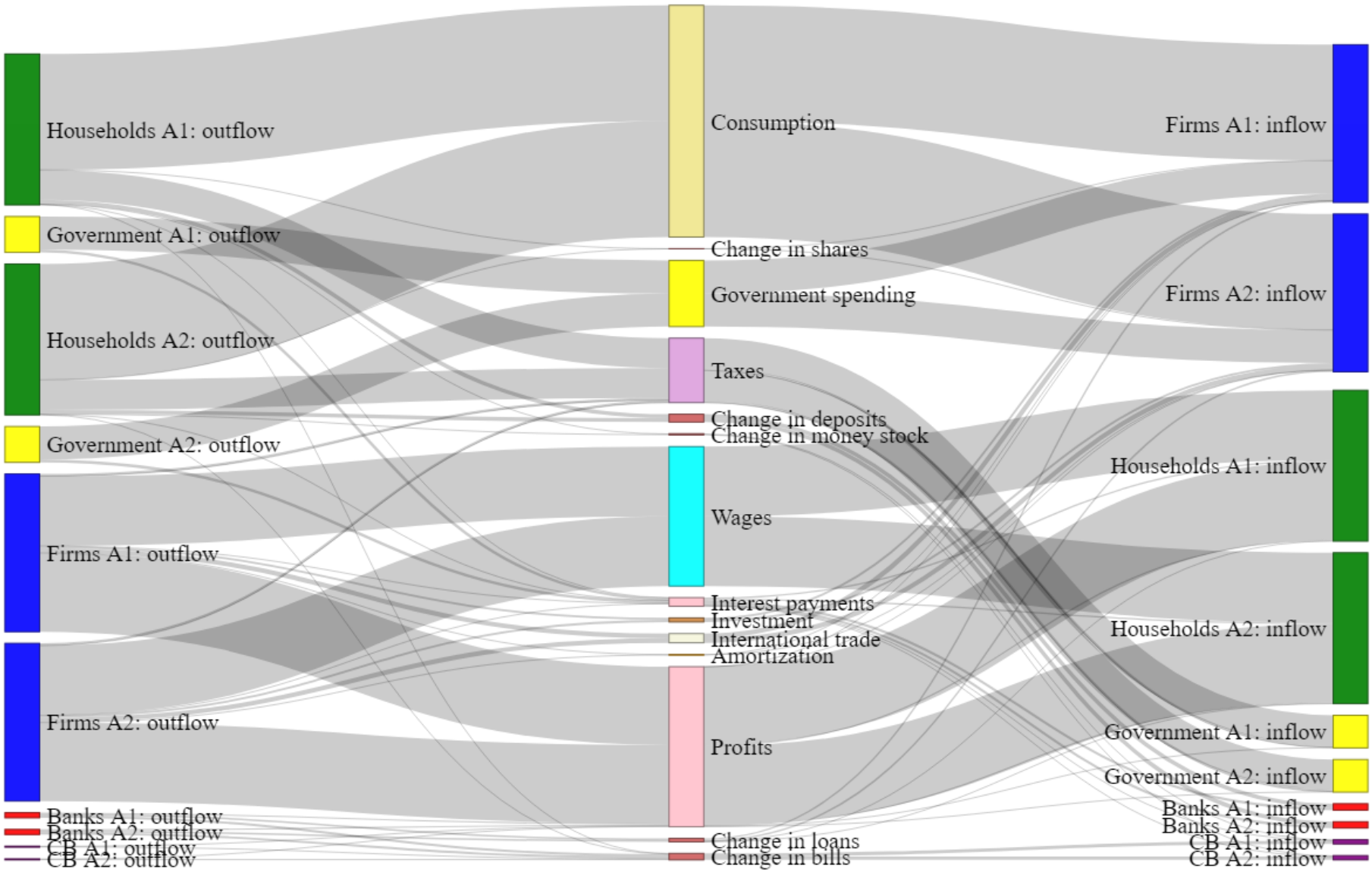


Figure 3. Cross-industry input-output flows (in $t = 20$)

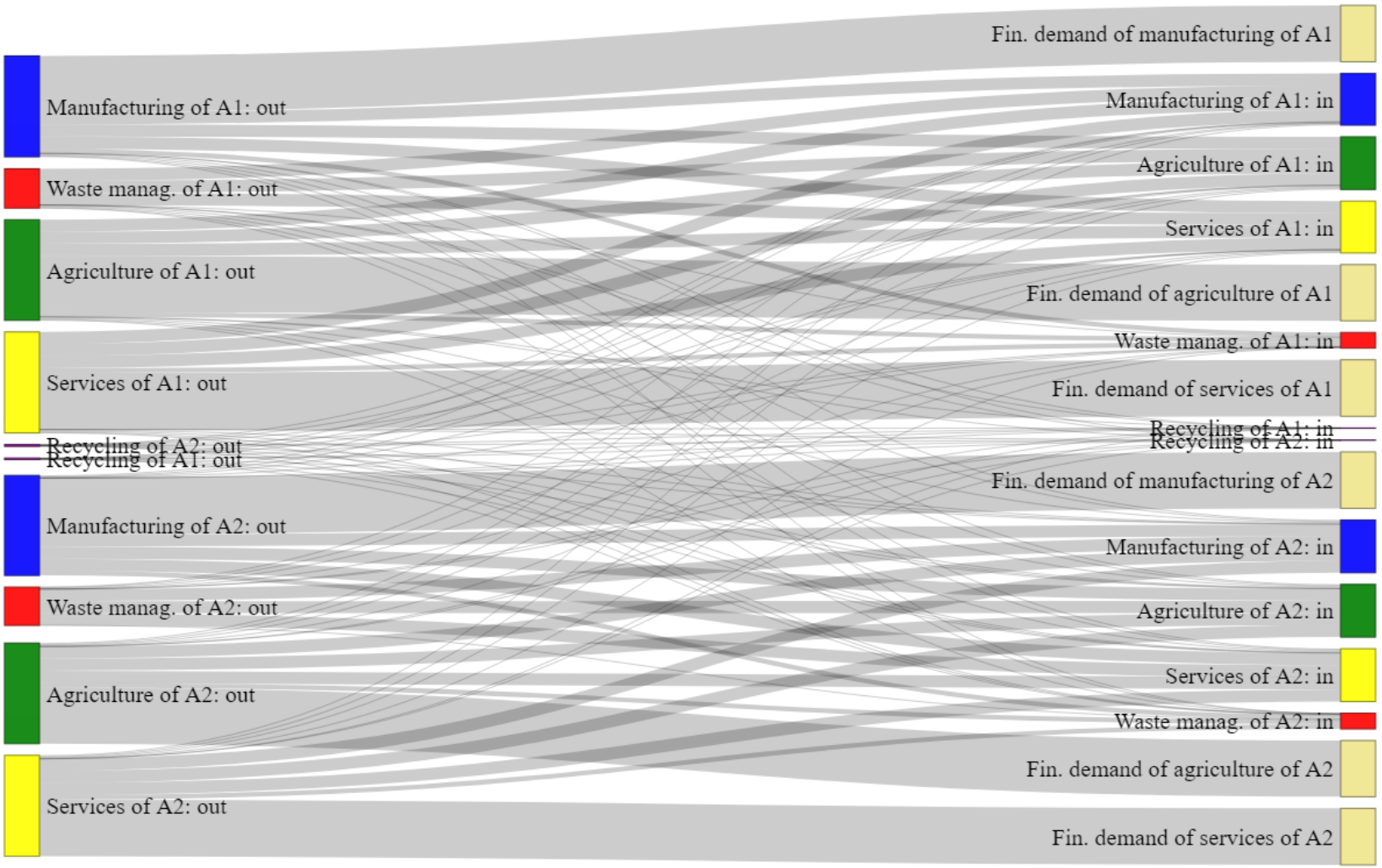


Figure 4. Physical flows of matter and energy (in $t = 20$)

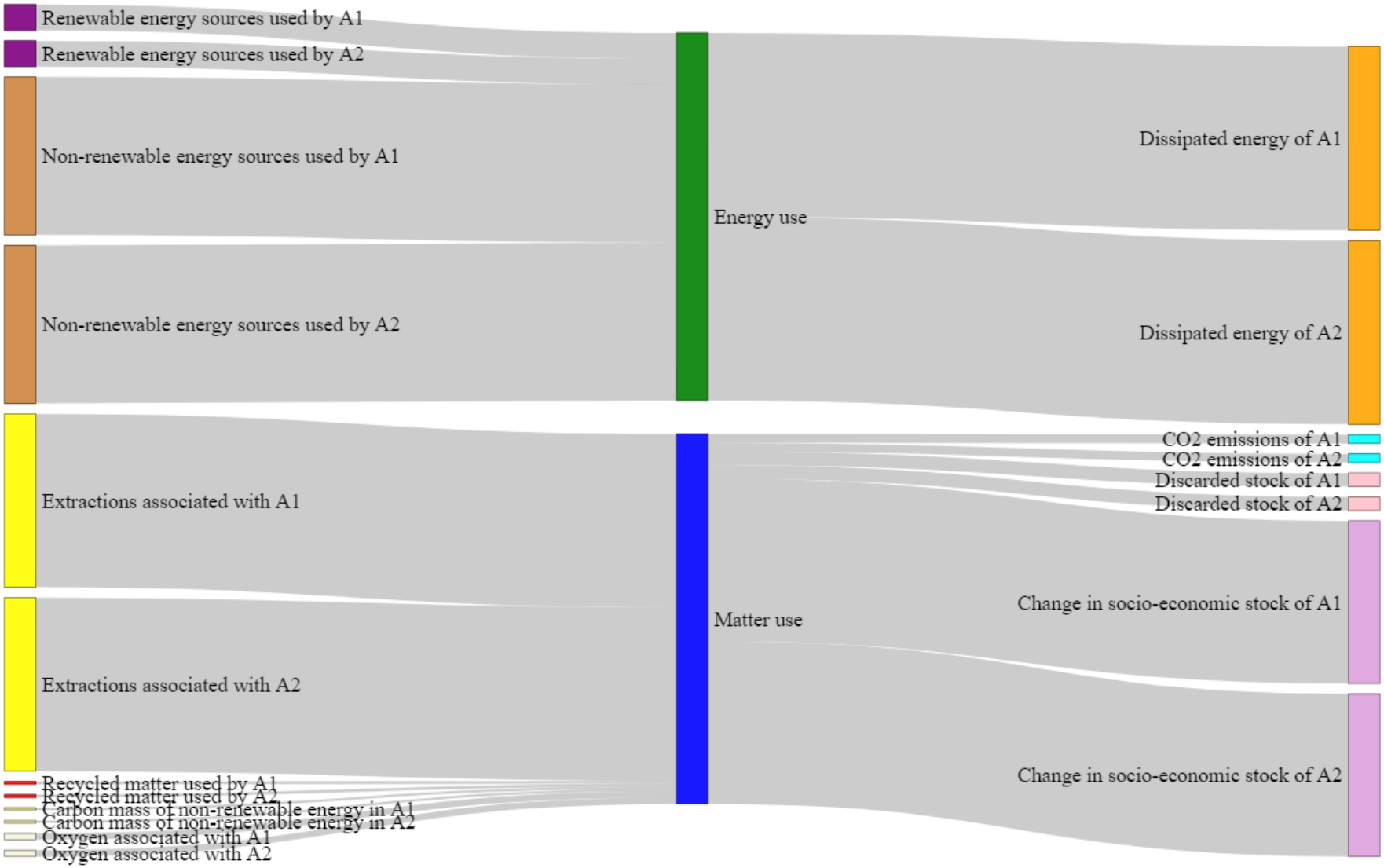


Figure 5. Adjustment of selected variables to steady state

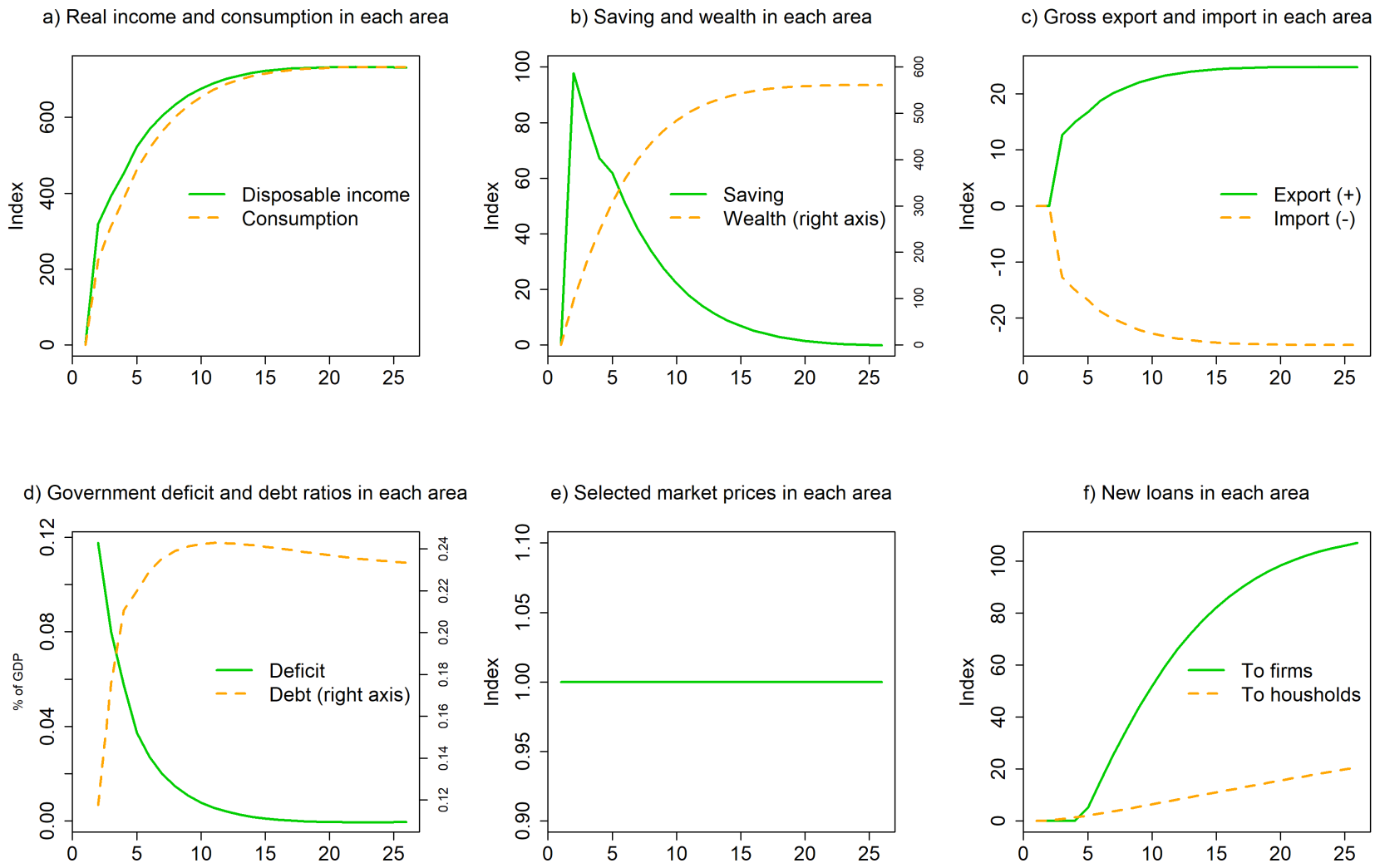
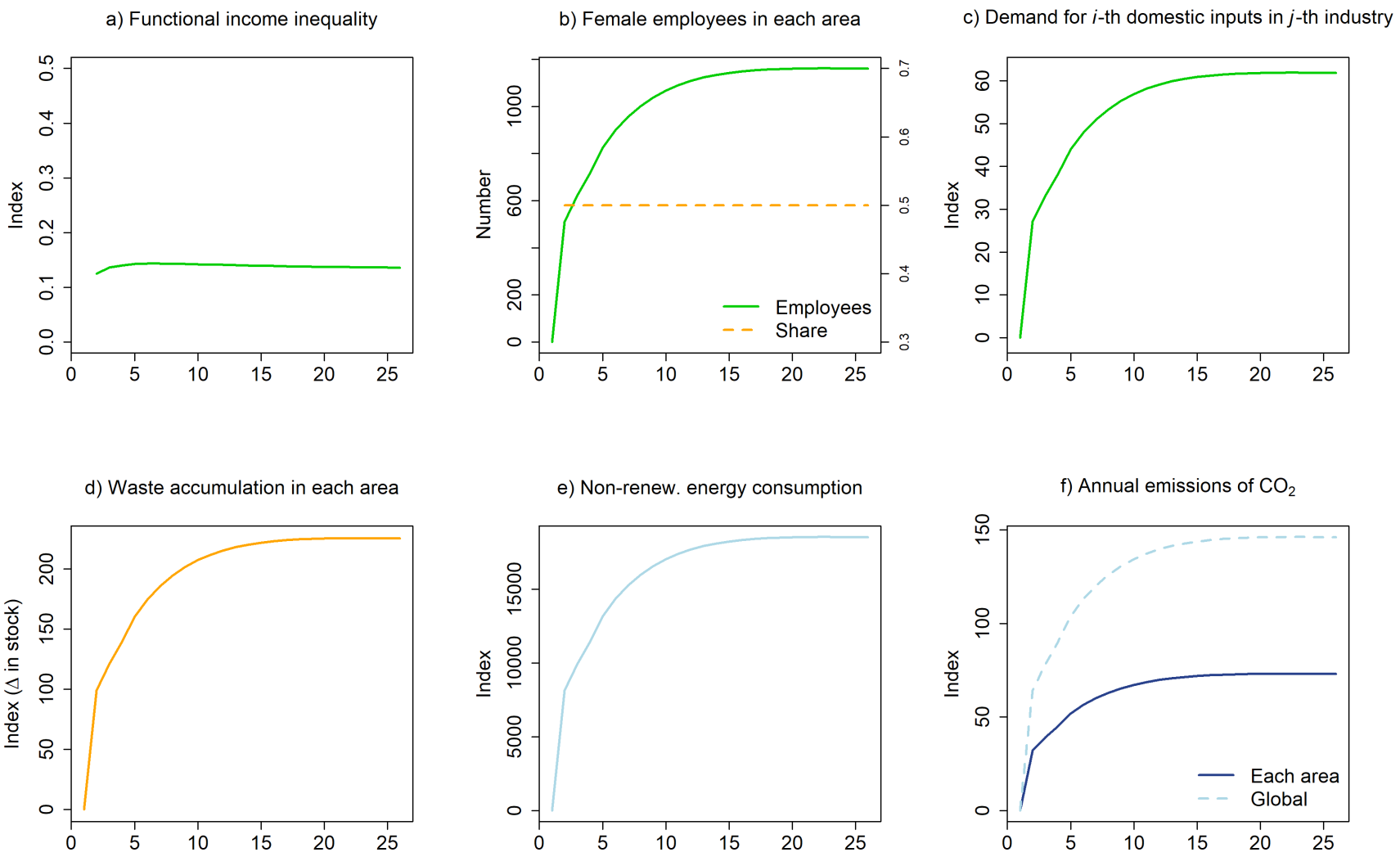


Figure 6. Adjustment of selected variables to steady state



The circular economy (CE)

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- If waste is not recycled, the global matrix of technical coefficients is:

$$\mathbf{A} = \left(\begin{array}{ccccc|ccccc} a_{11} & a_{12} & a_{13} & a_{14} & 0 & a_{16} & a_{17} & a_{18} & a_{19} & 0 \\ a_{21} & a_{22} & a_{23} & a_{24} & 0 & a_{26} & a_{27} & a_{28} & a_{29} & 0 \\ a_{31} & a_{32} & a_{33} & a_{34} & 0 & a_{36} & a_{37} & a_{38} & a_{39} & 0 \\ a_{41} & a_{42} & a_{43} & a_{44} & 0 & a_{46} & a_{47} & a_{48} & a_{49} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \hline a_{61} & a_{62} & a_{63} & a_{64} & 0 & a_{66} & a_{67} & a_{68} & a_{69} & 0 \\ a_{71} & a_{72} & a_{73} & a_{74} & 0 & a_{76} & a_{77} & a_{78} & a_{79} & 0 \\ a_{81} & a_{82} & a_{83} & a_{84} & 0 & a_{86} & a_{87} & a_{88} & a_{89} & 0 \\ a_{91} & a_{92} & a_{93} & a_{94} & 0 & a_{96} & a_{97} & a_{98} & a_{99} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{array}\right)$$

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- A CE innovation implies a change in technical coefficients...

A simple CE innovation in Area 1

- The new matrix will be:

$$\mathbf{A'} = \left(\begin{array}{ccccc||ccccc}
a'_{11} \leq a_{11} & a'_{12} \leq a_{12} & a'_{13} \leq a_{13} & a'_{14} \leq a'_{14} & a'_{15} > 0 & a_{16} & a_{17} & a_{18} & a_{19} & 0 \\
a'_{21} \leq a_{21} & a'_{22} \leq a_{22} & a'_{23} \leq a_{23} & a'_{24} \leq a'_{24} & a'_{25} > 0 & a_{26} & a_{27} & a_{28} & a_{29} & 0 \\
a'_{31} \leq a_{31} & a'_{32} \leq a_{32} & a'_{33} \leq a_{33} & a'_{34} \leq a'_{34} & a'_{35} > 0 & a_{36} & a_{37} & a_{38} & a_{39} & 0 \\
a'_{41} \leq a_{41} & a'_{42} \leq a_{42} & a'_{43} \leq a_{43} & a'_{44} \leq a'_{44} & a'_{45} > 0 & a_{46} & a_{47} & a_{48} & a_{49} & 0 \\
a'_{51} > 0 & a'_{52} > 0 & a'_{53} > 0 & a'_{54} > 0 & 0 & a_{56} & a_{57} & a_{58} & a_{59} & 0 \\
\hline
a'_{61} \leq a_{61} & a'_{62} \leq a_{62} & a'_{63} \leq a_{63} & a'_{64} \leq a'_{64} & a'_{65} > 0 & a_{66} & a_{67} & a_{68} & a_{69} & 0 \\
a'_{71} \leq a_{71} & a'_{72} \leq a_{72} & a'_{73} \leq a_{73} & a'_{74} \leq a'_{74} & a'_{75} > 0 & a_{76} & a_{77} & a_{78} & a_{79} & 0 \\
a'_{81} \leq a_{81} & a'_{82} \leq a_{82} & a'_{83} \leq a_{83} & a'_{84} \leq a'_{84} & a'_{85} > 0 & a_{86} & a_{87} & a_{88} & a_{89} & 0 \\
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A simple CE innovation in Area 1

- The new matrix will be:

$$\mathbf{A'} = \left(\begin{array}{ccccc||ccccc} a'_{11} \leq a_{11} & a'_{12} \leq a_{12} & a'_{13} \leq a_{13} & a'_{14} \leq a'_{14} & a'_{15} > 0 & a_{16} & a_{17} & a_{18} & a_{19} & 0 \\ a'_{21} \leq a_{21} & a'_{22} \leq a_{22} & a'_{23} \leq a_{23} & a'_{24} \leq a'_{24} & a'_{25} > 0 & a_{26} & a_{27} & a_{28} & a_{29} & 0 \\ a'_{31} \leq a_{31} & a'_{32} \leq a_{32} & a'_{33} \leq a_{33} & a'_{34} \leq a'_{34} & a'_{35} > 0 & a_{36} & a_{37} & a_{38} & a_{39} & 0 \\ a'_{41} \leq a_{41} & a'_{42} \leq a_{42} & a'_{43} \leq a_{43} & a'_{44} \leq a'_{44} & a'_{45} > 0 & a_{46} & a_{47} & a_{48} & a_{49} & 0 \\ a'_{51} > 0 & a'_{52} > 0 & a'_{53} > 0 & a'_{54} > 0 & 0 & a_{56} & a_{57} & a_{58} & a_{59} & 0 \\ \hline a'_{61} \leq a_{61} & a'_{62} \leq a_{62} & a'_{63} \leq a_{63} & a'_{64} \leq a'_{64} & a'_{65} > 0 & a_{66} & a_{67} & a_{68} & a_{69} & 0 \\ a'_{71} \leq a_{71} & a'_{72} \leq a_{72} & a'_{73} \leq a_{73} & a'_{74} \leq a'_{74} & a'_{75} > 0 & a_{76} & a_{77} & a_{78} & a_{79} & 0 \\ a'_{81} \leq a_{81} & a'_{82} \leq a_{82} & a'_{83} \leq a_{83} & a'_{84} \leq a'_{84} & a'_{85} > 0 & a_{86} & a_{87} & a_{88} & a_{89} & 0 \\ a'_{91} \leq a_{91} & a'_{92} \leq a_{92} & a'_{93} \leq a_{93} & a'_{94} \leq a'_{94} & a'_{95} > 0 & a_{96} & a_{97} & a_{98} & a_{99} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{array}\right)$$

- Fall in coefficients defining the quantities of manufacturing and agricultural products and services used as inputs in first area ($\bullet$)

A simple CE innovation in Area 1

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a'_{11} \leq a_{11} & a'_{12} \leq a_{12} & a'_{13} \leq a_{13} & a'_{14} \leq a'_{14} & a'_{15} > 0 & a_{16} & a_{17} & a_{18} & a_{19} & 0 \\
a'_{21} \leq a_{21} & a'_{22} \leq a_{22} & a'_{23} \leq a_{23} & a'_{24} \leq a'_{24} & a'_{25} > 0 & a_{26} & a_{27} & a_{28} & a_{29} & 0 \\
a'_{31} \leq a_{31} & a'_{32} \leq a_{32} & a'_{33} \leq a_{33} & a'_{34} \leq a'_{34} & a'_{35} > 0 & a_{36} & a_{37} & a_{38} & a_{39} & 0 \\
a'_{41} \leq a_{41} & a'_{42} \leq a_{42} & a'_{43} \leq a_{43} & a'_{44} \leq a'_{44} & a'_{45} > 0 & a_{46} & a_{47} & a_{48} & a_{49} & 0 \\
a'_{51} > 0 & a'_{52} > 0 & a'_{53} > 0 & a'_{54} > 0 & 0 & a_{56} & a_{57} & a_{58} & a_{59} & 0 \\
\hline
a'_{61} \leq a_{61} & a'_{62} \leq a_{62} & a'_{63} \leq a_{63} & a'_{64} \leq a'_{64} & a'_{65} > 0 & a_{66} & a_{67} & a_{68} & a_{69} & 0 \\
a'_{71} \leq a_{71} & a'_{72} \leq a_{72} & a'_{73} \leq a_{73} & a'_{74} \leq a'_{74} & a'_{75} > 0 & a_{76} & a_{77} & a_{78} & a_{79} & 0 \\
a'_{81} \leq a_{81} & a'_{82} \leq a_{82} & a'_{83} \leq a_{83} & a'_{84} \leq a'_{84} & a'_{85} > 0 & a_{86} & a_{87} & a_{88} & a_{89} & 0 \\
a'_{91} \leq a_{91} & a'_{92} \leq a_{92} & a'_{93} \leq a_{93} & a'_{94} \leq a'_{94} & a'_{95} > 0 & a_{96} & a_{97} & a_{98} & a_{99} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{array}\right)$$

- Fall in coefficients defining the quantities of manufacturing and agricultural products and services used as inputs in first area (•)
- Domestic waste now enters the production process in first area (•)

A simple CE innovation in Area 1

- The new matrix will be:

$$\mathbf{A'} = \left(\begin{array}{ccccc|ccccc}
a'_{11} \leq a_{11} & a'_{12} \leq a_{12} & a'_{13} \leq a_{13} & a'_{14} \leq a'_{14} & a'_{15} > 0 & a_{16} & a_{17} & a_{18} & a_{19} & 0 \\
a'_{21} \leq a_{21} & a'_{22} \leq a_{22} & a'_{23} \leq a_{23} & a'_{24} \leq a'_{24} & a'_{25} > 0 & a_{26} & a_{27} & a_{28} & a_{29} & 0 \\
a'_{31} \leq a_{31} & a'_{32} \leq a_{32} & a'_{33} \leq a_{33} & a'_{34} \leq a'_{34} & a'_{35} > 0 & a_{36} & a_{37} & a_{38} & a_{39} & 0 \\
a'_{41} \leq a_{41} & a'_{42} \leq a_{42} & a'_{43} \leq a_{43} & a'_{44} \leq a'_{44} & a'_{45} > 0 & a_{46} & a_{47} & a_{48} & a_{49} & 0 \\
a'_{51} > 0 & a'_{52} > 0 & a'_{53} > 0 & a'_{54} > 0 & 0 & a_{56} & a_{57} & a_{58} & a_{59} & 0 \\
\hline
a'_{61} \leq a_{61} & a'_{62} \leq a_{62} & a'_{63} \leq a_{63} & a'_{64} \leq a'_{64} & a'_{65} > 0 & a_{66} & a_{67} & a_{68} & a_{69} & 0 \\
a'_{71} \leq a_{71} & a'_{72} \leq a_{72} & a'_{73} \leq a_{73} & a'_{74} \leq a'_{74} & a'_{75} > 0 & a_{76} & a_{77} & a_{78} & a_{79} & 0 \\
a'_{81} \leq a_{81} & a'_{82} \leq a_{82} & a'_{83} \leq a_{83} & a'_{84} \leq a'_{84} & a'_{85} > 0 & a_{86} & a_{87} & a_{88} & a_{89} & 0 \\
a'_{91} \leq a_{91} & a'_{92} \leq a_{92} & a'_{93} \leq a_{93} & a'_{94} \leq a'_{94} & a'_{95} > 0 & a_{96} & a_{97} & a_{98} & a_{99} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{array}\right)$$

- Fall in coefficients defining the quantities of manufacturing and agricultural products and services used as inputs in first area (•)
- Domestic waste now enters the production process in first area (•)
- Manufacturing and agricultural products and services are used as inputs in waste industry of first area (•)

The role of the government sector

- There is a tendency for current technical coefficients to converge to target CE values over time:

$$a_{ij} = a_{ij,-1} + \gamma_A^z \cdot (a'_{ij,-1} - a_{ij,-1}) \tag{32}$$

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- The average speed of convergence of technical coefficients to their target values is a linear, positive function of industry-specific government expenditures

Figure 6. CE-oriented gov. spending in Area 1

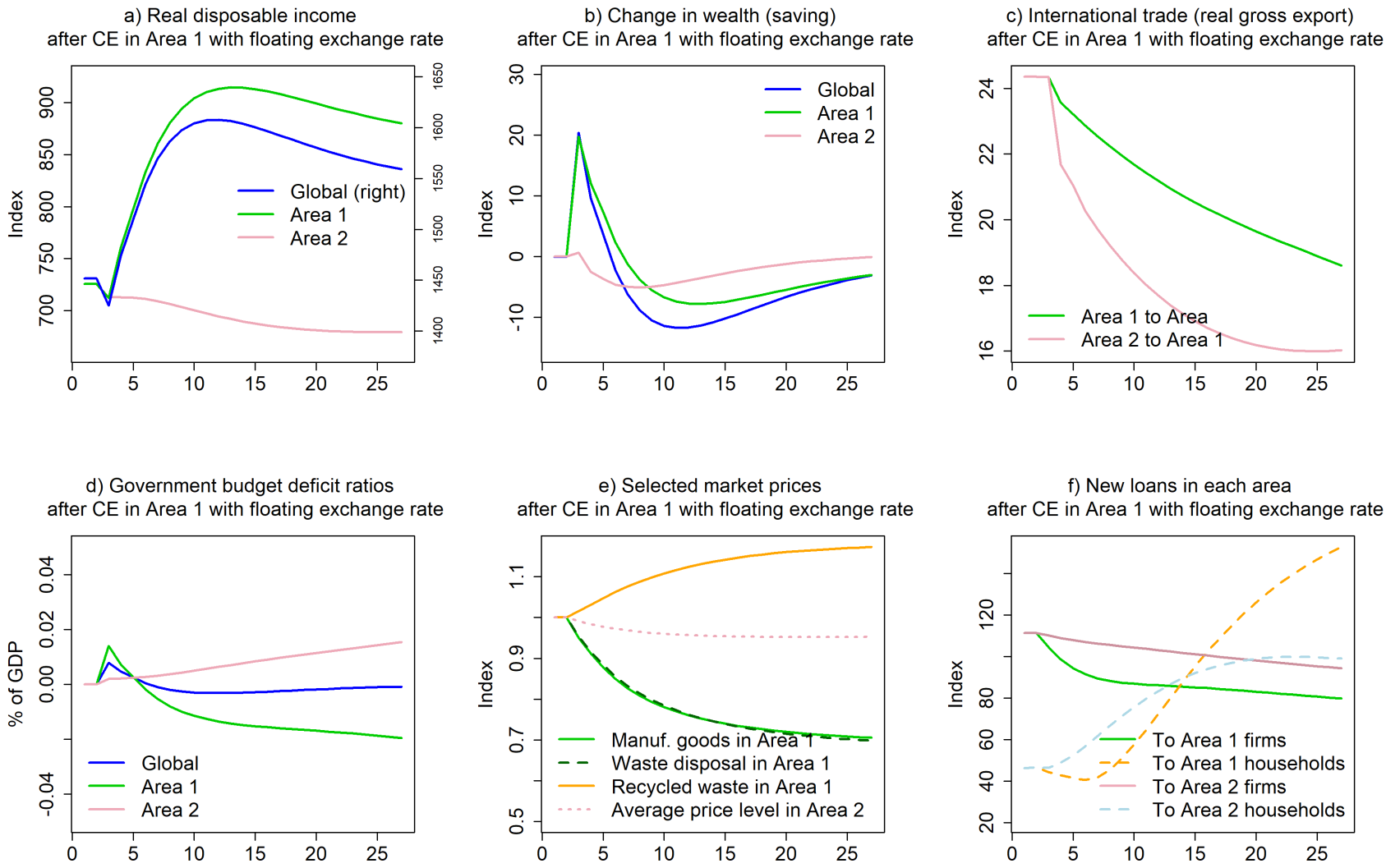
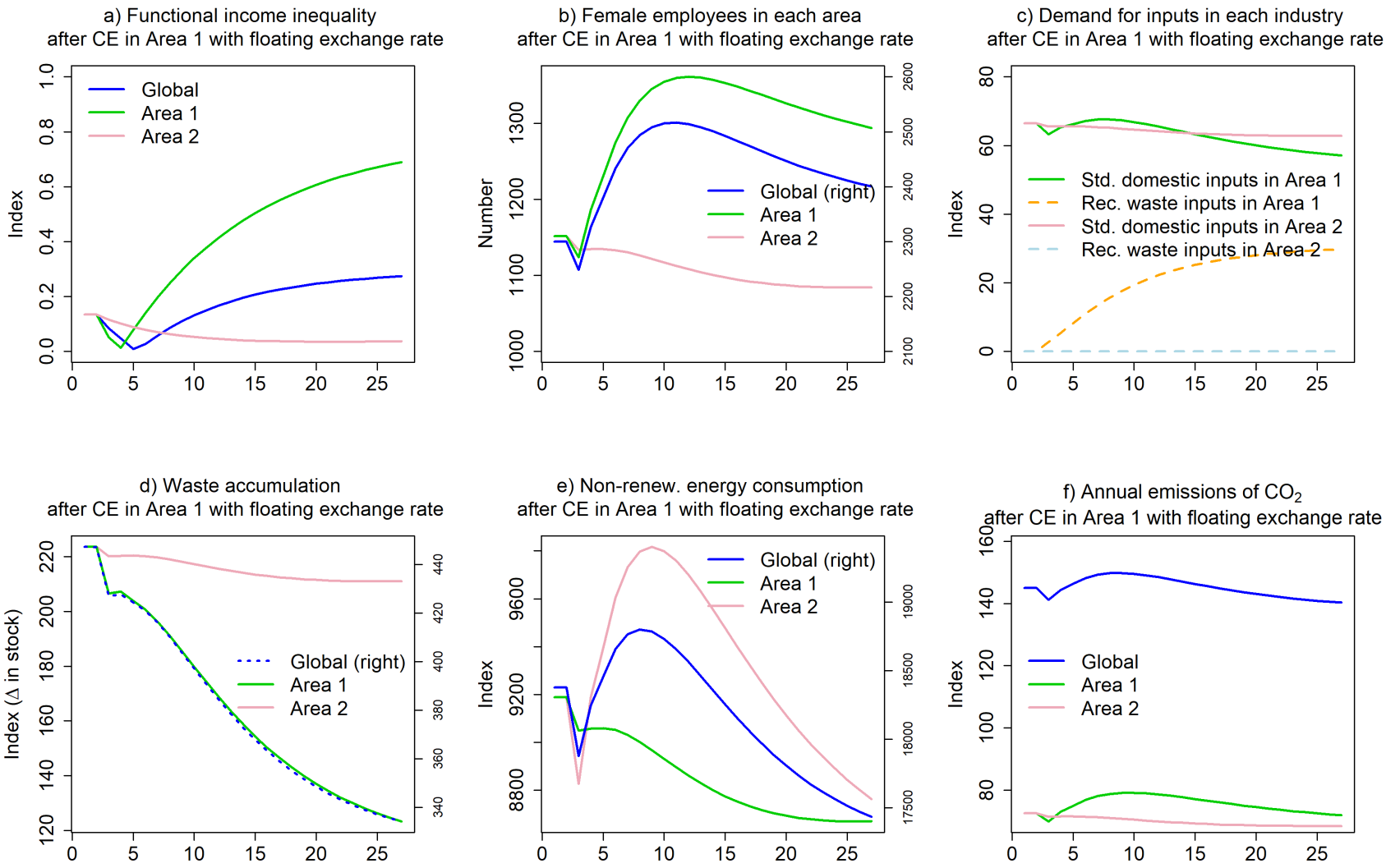


Figure 7. CE-oriented gov. spending in Area 1 (cont'd)



Final remarks

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  c) Calibrate using real data (e.g. *Exiobase*) / estimate coefficients

Final remarks

- The model provides a benchmark for other MA-IO-SFC models
- Next steps:
  a) Introduce landfill limit and consumption constraints
  b) Make additional experiments
  c) Calibrate using real data (e.g. *Exiobase*) / estimate coefficients
  d) Turn into *n*-area model

Thank you

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