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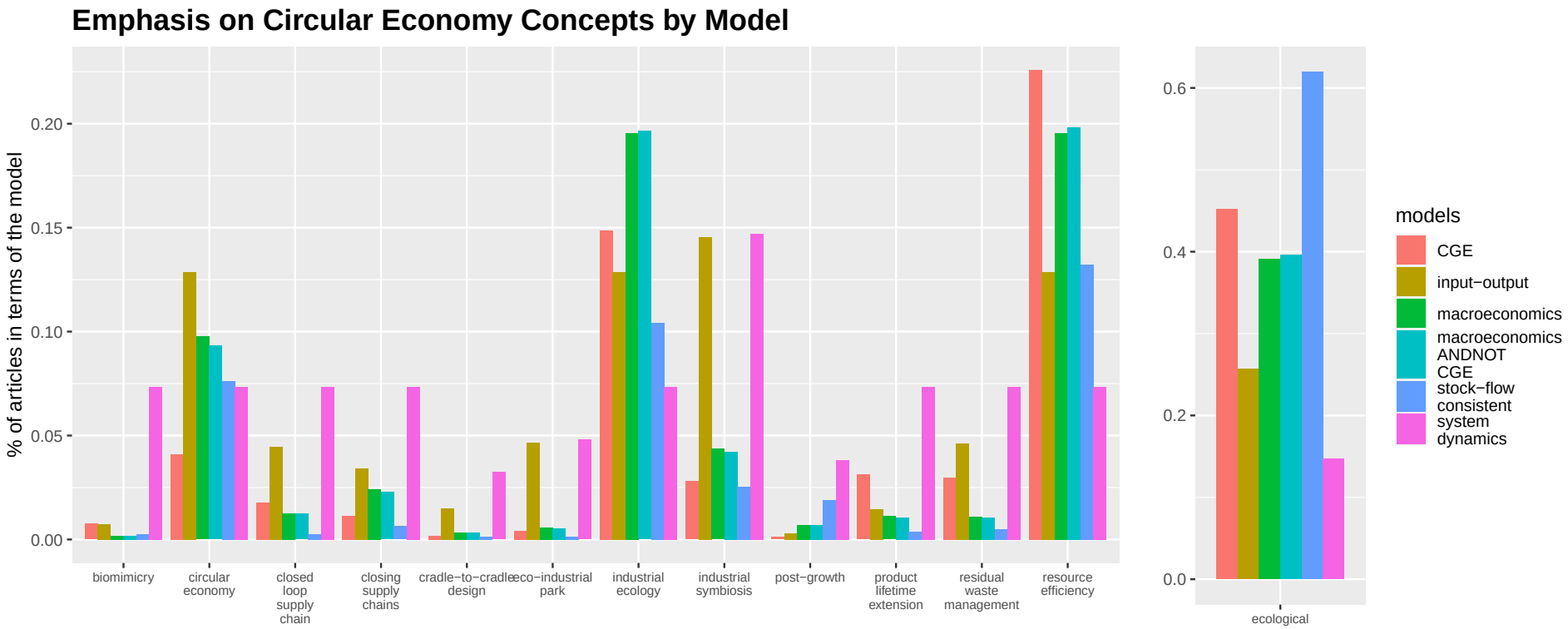
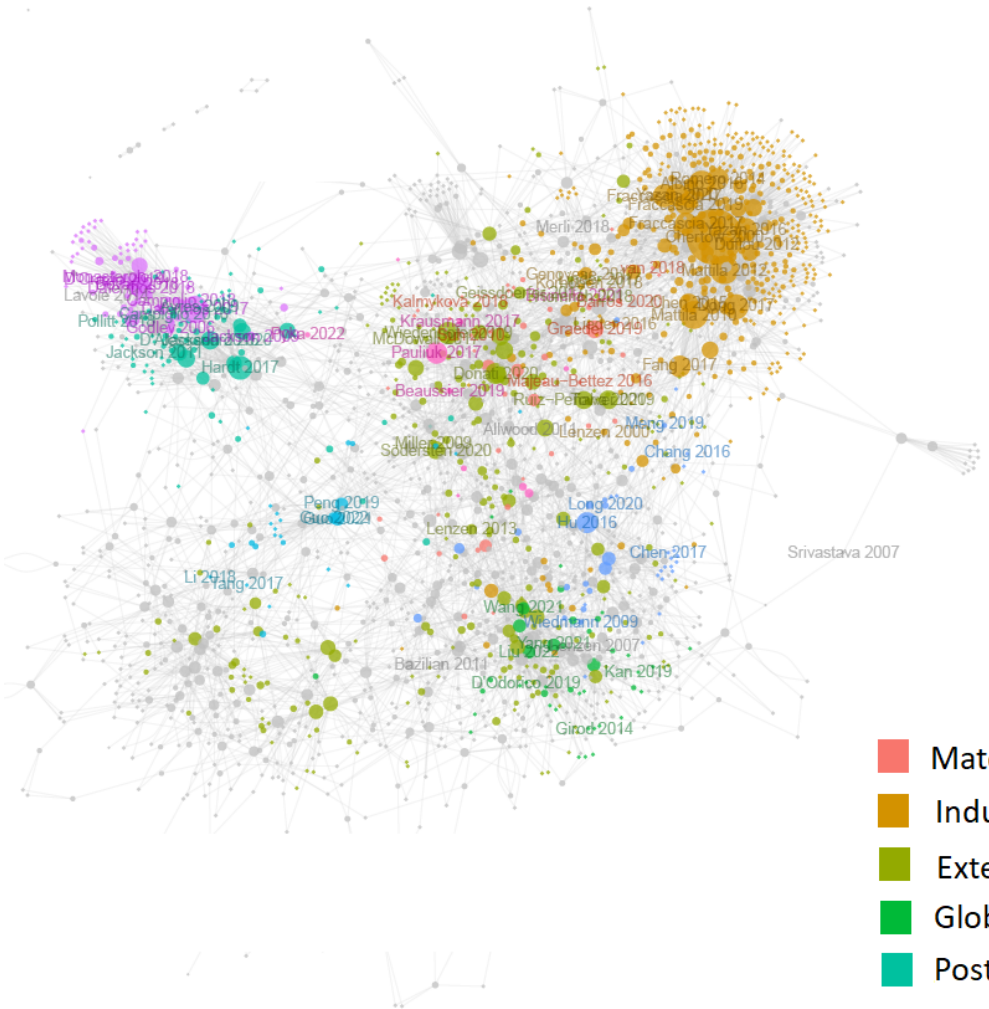
- We have focused on both topics and modeling techniques
- We have identified, discussed, and assessed the most popular/promising tools (to model the transition...)

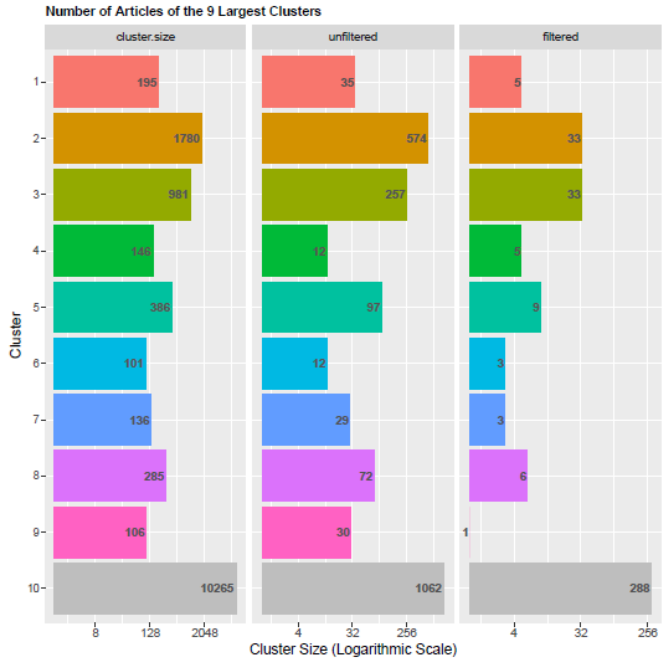
Figure A1. Concepts and models



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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  2) SFC models. Pros: dynamics, finance. Cons: homogeneous output
- In principle, we can disaggregate SFC models by crossbreeding them with IO models... (Hardt and O'Neill 2017)

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  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), 250 periods, 100 iterations

Accounting structure

Table 1: Balance sheet

	Households	Firms	Government	Banks	CB	Foreign	Total
Cash	✓				✓		0
Advances				✓	✓		0
Deposits	✓			✓			0
Loans		✓		✓			0
Bills	✓		✓	✓	✓	✓	0
Capital stock		✓					✓
Net financial wealth	✓		✓			✓	✓
Total	0	0	0	0	0	0	0

Table 2: Transactions-flow matrix

	Households	Firms		Government	Banks	CB	Foreign	Tot.
		Current	Capital					
Consumption	✓	✓						0
Investment		✓	✓					0
Government spending		✓		✓				0
Export		✓					✓	0
Import		✓					✓	0
[Value added]		[✓]						0
Wage bill	✓	✓						0
Corporate profit	✓	✓						0
Amortization		✓	✓					0
Bank profit	✓				✓			0
Tax revenue	✓			✓				0
Interests on deposits	✓				✓			0
Interests on loans		✓			✓			0
Interests on bills	✓			✓	✓		✓	0
Change in cash	✓					✓		0
Change in advances					✓	✓		0
Change in deposits	✓				✓			0
Change in loans			✓		✓			0
Change in bills	✓			✓	✓	✓	✓	0
Total	0	0	0	0	0	0	0	0

Table 3: Input-output matrix

	Manuf.	Agric.	Serv.	Recyc.	Total	Fin. dem.	Tot. output
Manufacturing (production)	✓	✓	✓	✓	✓	✓	✓
Agriculture (production)	✓	✓	✓	✓	✓	✓	✓
Services (provision)	✓	✓	✓	✓	✓	✓	✓
Recycling (production)	✓	✓	✓	✓	✓	✓	✓
Value added	✓	✓	✓	✓	✓		
~ Disposable income	✓	✓	✓	✓	✓		
~ Tax revenue	✓	✓	✓	✓	✓		
~ Interest payments (-)	✓	✓	✓	✓	✓		
Import (production)	✓	✓	✓	✓	✓	✓	
Total output	✓	✓	✓	✓	✓	✓	✓

Selected equations: households

- Total "real" consumption is:

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

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- Households' total disposable income:

$$YD = w \cdot N + F_f + F_b + r_{m,-1} \cdot M_{h,-1} + r_{b,-1} \cdot B_{h,-1} - T \tag{2}$$

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- Disposable labour income in each industry j is:

$$YD_j^w = w \cdot N_j \cdot (1 - \theta), \quad with : j = 1, 2, 3 \tag{3}$$

Selected equations: firms (current)

- Let us consider a 3×3 production. The final demand vector is:

$$\mathbf{d} = \begin{pmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \end{pmatrix} \cdot c + \begin{pmatrix} \iota_1 \\ \iota_2 \\ \iota_3 \end{pmatrix} \cdot i_d + \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \end{pmatrix} \cdot gov + \begin{pmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \end{pmatrix} \cdot exp \tag{4}$$

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- The gross output vector is:

$$\mathbf{x} = \mathbf{A} \cdot \mathbf{x} + \mathbf{d} = (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{d}, \ with : \mathbf{A} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \tag{5}$$

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- The net domestic income of home country is:

$$Y_n = \mathbf{p}^T \cdot \mathbf{d} - \mathbf{p}^T \cdot (\mathbf{m} \odot \mathbf{d}) \tag{6}$$

Selected equations: consumption composition

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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:

$$\beta_3 = \beta_{3,-1} + \beta_{31} \cdot \frac{YD^w_{-1}}{p_{3,-1}} + \beta_{32} \cdot \frac{YD^c_{-1}}{p_{3,-1}} \tag{8}$$

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

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

Selected equations: firms (capital)

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

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

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

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

$$L_f = L_{f,-1} + i_d \cdot p_1 - AF, \quad with: AF = \delta \cdot k_{-1} \cdot p_1 \tag{12}$$

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- Bank holdings of government bills are:

$$\textit{if } M_s \geq L_s \textit{ then } B_b = M_s - L_s \textit{ else } B_b = 0 \tag{15}$$

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- whereas advances obtained from the CB are:

$$if\ M_s < L_s\ then\ A_d = L_s - M_s\ else\ A_d = 0 \tag{16}$$

Selected equations: government and CB

- The supply of government bills is:

$$B_s = B_{s,-1} + gov \cdot p_G - T + r_b \cdot (B_h + B_b + B_{fo}) \tag{17}$$

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- At the end of each period, the central bank holds the residual amount of bills:

$$B_{cb} = B_s - B_h - B_b - B_{fo} \tag{18}$$

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- Therefore, cash supply is:

$$H_s = H_{s,-1} + (B_{cb} - B_{cb,-1}) + (A_s - A_{s,-1}) \tag{19}$$

Selected equations: prices

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

$$\mathbf{p}^* = w \cdot \mathbf{l} + \mathbf{p}^* \cdot \mathbf{A} \odot \mathbf{m}^* \tag{20}$$

where: $\mathbf{m}^* = \{1 + \mu_j^*\}$

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

$$p_A = \mathbf{p}^T \cdot \beta, \quad with : \beta = \begin{pmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \end{pmatrix} \tag{22}$$

Selected equations: portfolio choices

- Households' demand for bills is:

$$\frac{B_h}{V} = \lambda_0 - \lambda_1 \cdot r_m + \lambda_2 \cdot r_b - \lambda_3 \cdot \frac{YD}{V} \tag{23}$$

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$$M_h = V - B_h - H_h \tag{25}$$

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- The redundant equation is:

$$H_h = H_s$$

Selected equations: waste and emissions

- The quantity of waste generated by each (domestic) industry is:

$$WA_j = WA_{j,-1} + (x_j - x_{j,fo}) \cdot (\zeta_j - a_{j,4}) \tag{26}$$

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- CO_2 emissions generated by each (domestic) industry are:

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where $\varepsilon_j = Ej_j/x_j =$ industry-specific energy intensity coefficient, and $\beta_e = Gt/Ej =$ common CO_2 intensity coefficient.

Selected equations: waste and emissions

- The quantity of waste generated by each (domestic) industry is:

$$WA_j = WA_{j,-1} + (x_j - x_{j,fo}) \cdot (\zeta_j - a_{j,4}) \tag{26}$$

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- Atmospheric CO_2 concentration is then calculated using carbon cycle equations.

Figure 1. Sankey diagram of transactions (in $t = 8$)

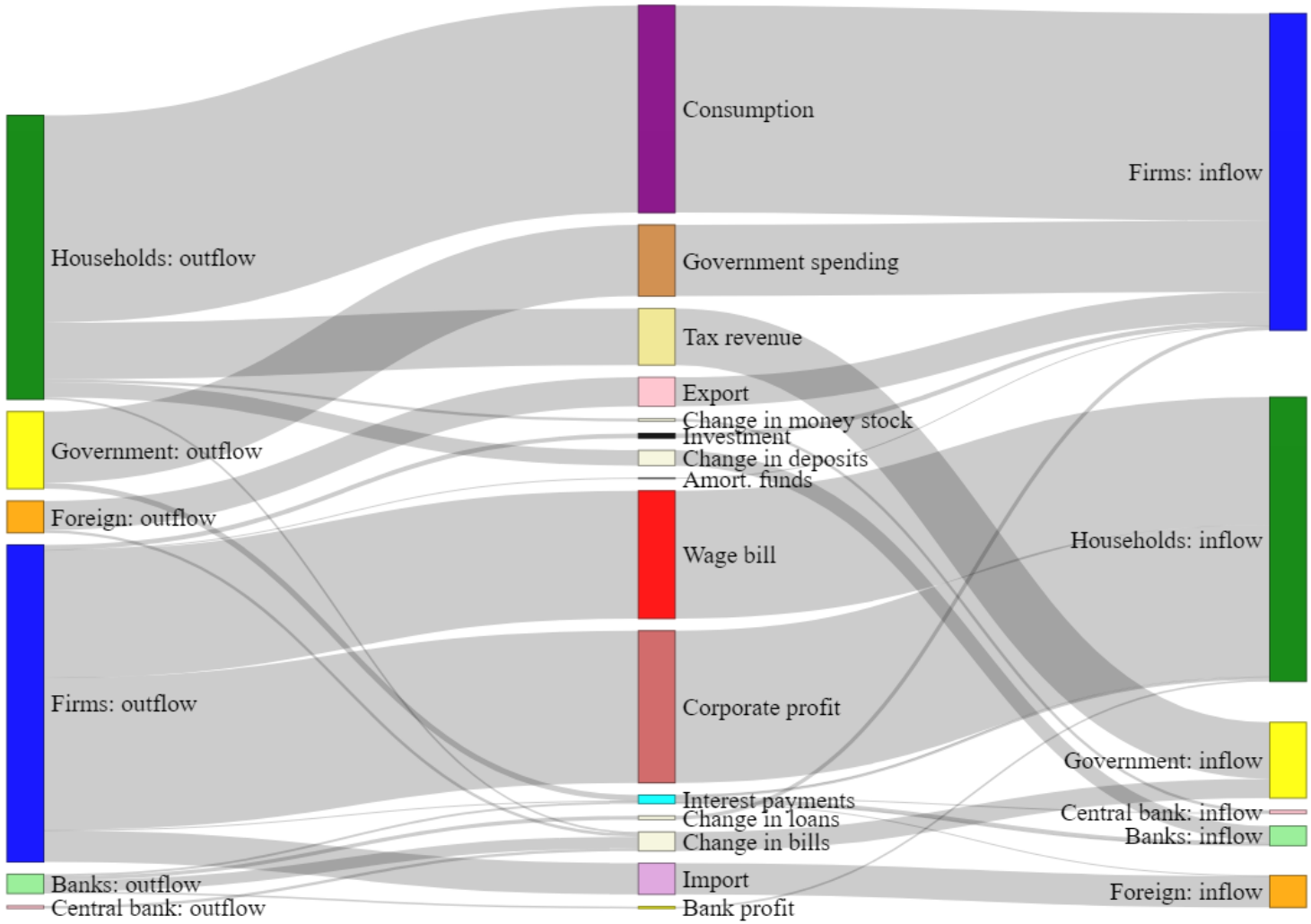


Figure 2. Cross-industry "physical" flows (in $t_s = 5$)

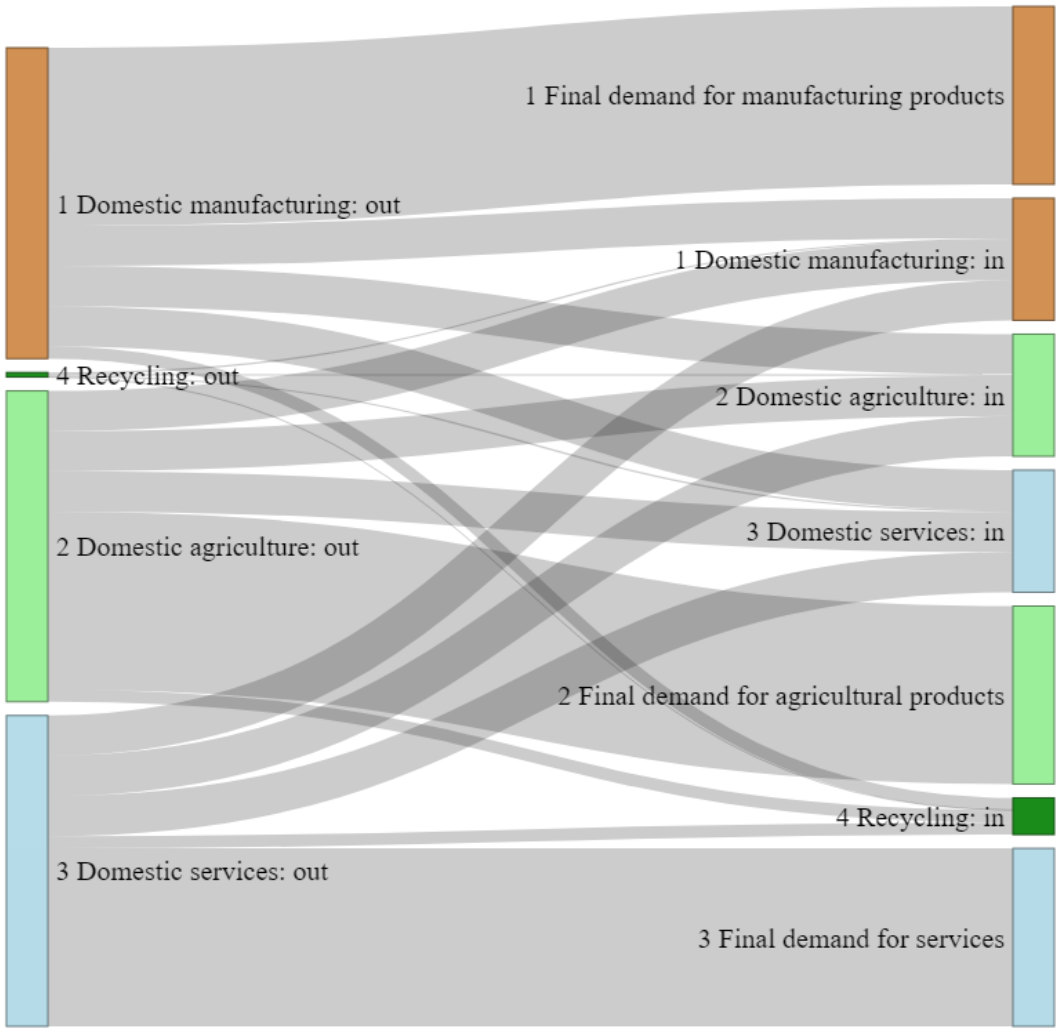


Figure 3. Model dynamics: baseline

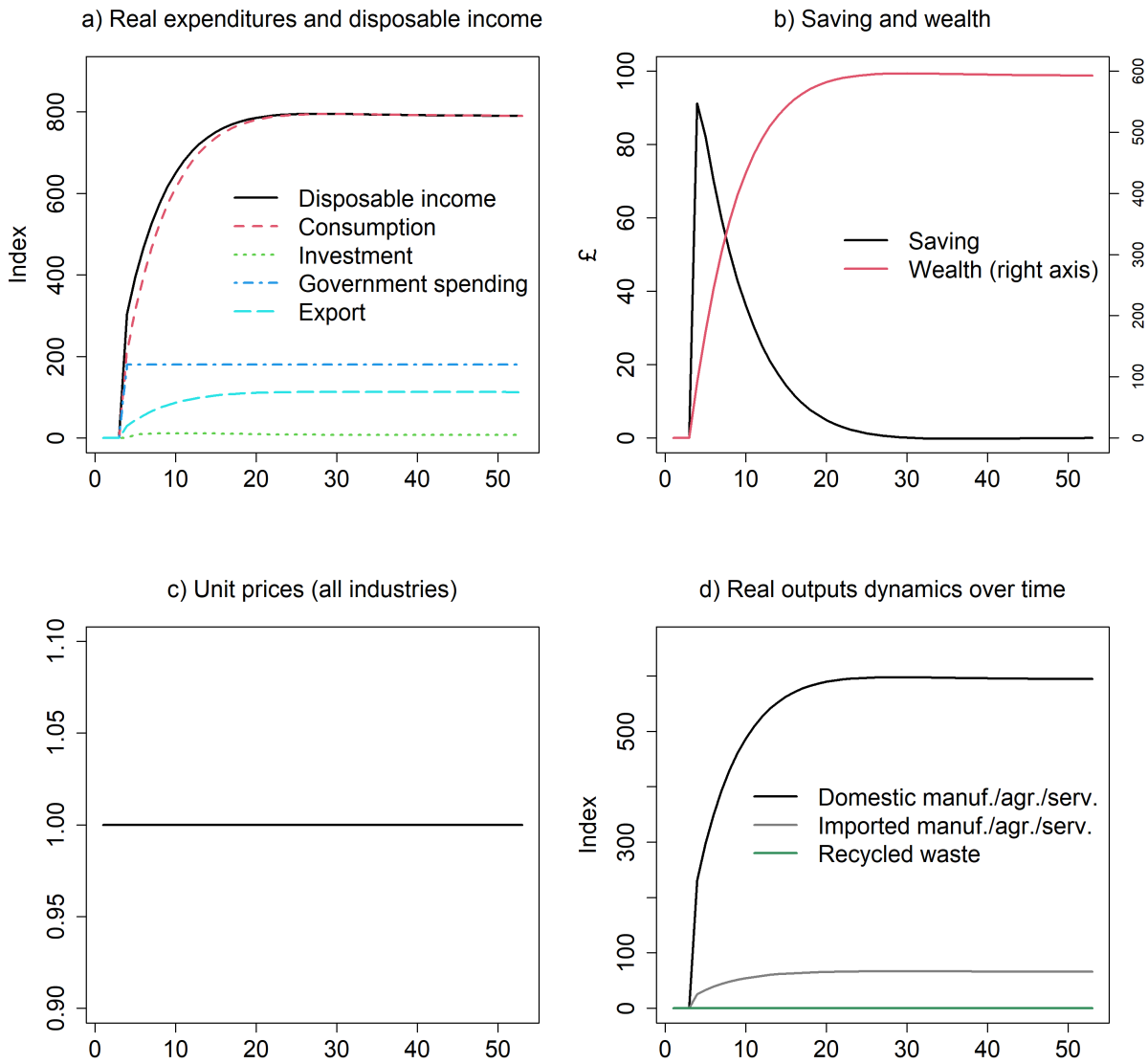
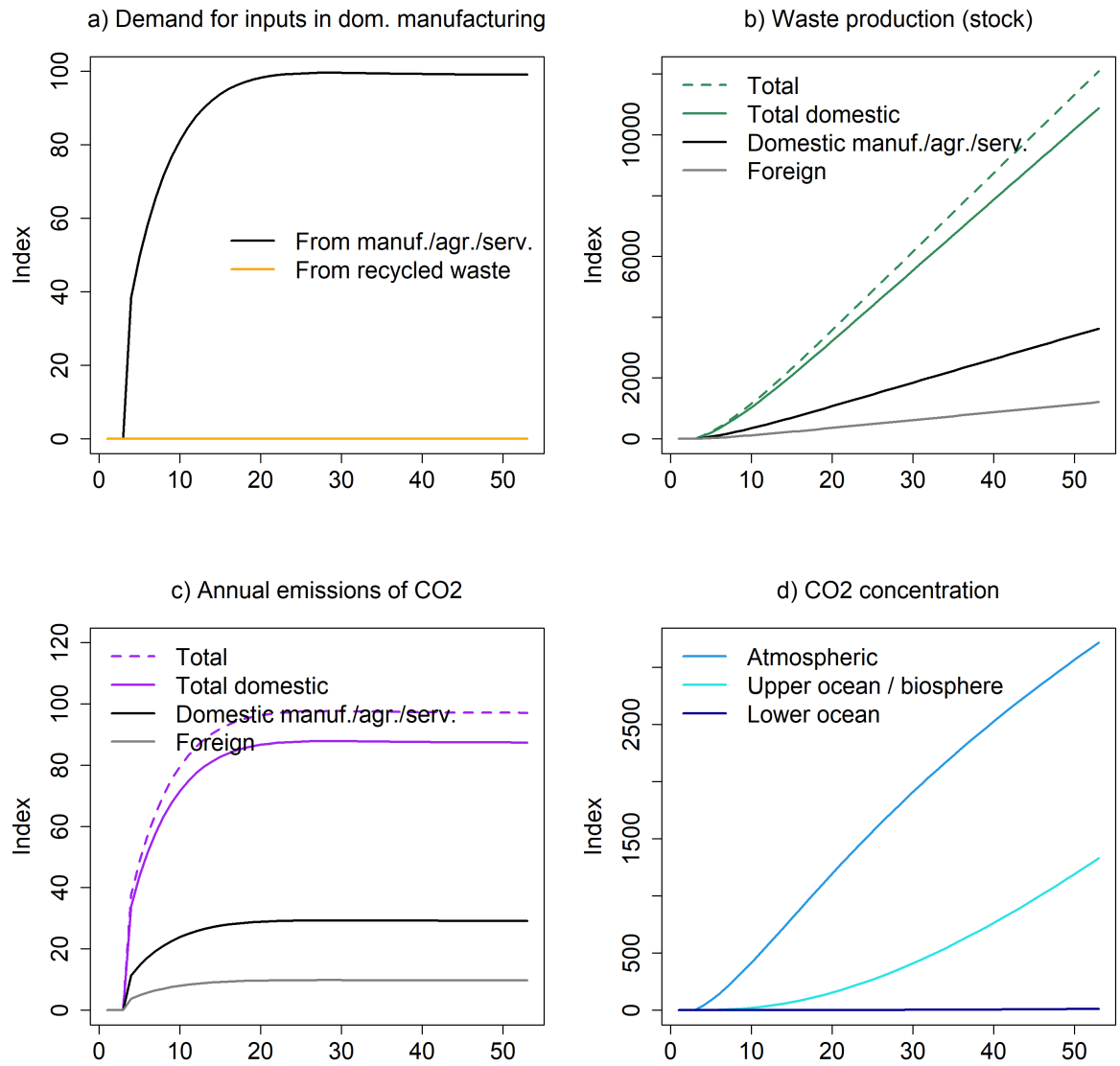


Figure 4. Model dynamics: baseline (cont'd)



Nominal value of assets and liabilities

Table 1: Balance sheet, current prices, $t = 8$ (baseline)

	Households	Firms	Government	Banks	CB	Foreign	Total
Cash	46.43	0	0	0	-46.43	0	0
Advances	0	0	0	0	0	0	0
Deposits	272.29	0	0	-272.29	0	0	0
Loans	0	-36.62	0	36.62	0	0	0
Bills	35.41	0	-367.09	235.67	46.43	49.58	0
Capital stock	0	36.62	0	0	0	0	36.62
Net financial wealth	-354.13	0	367.09	0	0	-49.58	-36.62
Total	0	0	0	0	0	0	0

Money transactions and changes in stocks

Table 2: Transactions-flow matrix, current prices, $t = 8$ (baseline)

	Households	Firms		Government	Banks	CB	Foreign	Tot.
		Current	Capital					
Consumption	-522.91	522.91	0	0	0	0	0	0
Investment	0	11.55	-11.55	0	0	0	0	0
Government spending	0	180	0	-180	0	0	0	0
Export	0	73.29	0	0	0	0	-73.29	0
Import	0	-78.77	0	0	0	0	78.77	0
[Value added]	0	[708.97]	0	0	0	0	0	0
Wage bill	322.26	-322.26	0	0	0	0	0	0
Corporate profit	383.80	-383.8	0	0	0	0	0	0
Amortization	0	-1.83	1.83	0	0	0	0	0
Bank profit	4.67	0	0	0	-4.67	0	0	0
Tax revenue	-142.97	0	0	142.97	0	0	0	0
Interests on deposits	4.67	0	0	0	-4.67	0	0	0
Interests on loans	0	-1.08	0	0	1.08	0	0	0
Interests on bills	1.21	0	0	-11.18	8.27	0	1.70	0
Change in cash	-6.93	0	0	0	0	6.93	0	0
Change in advances	0	0	0	0	0	0	0	0
Change in deposits	-38.73	0	0	0	38.73	0	0	0
Change in loans	0	0	9.71	0	-9.71	0	0	0
Change in bills	-5.07	0	0	48.20	-29.02	-6.93	-7.18	0
Total	0	0	0	0	0	0	0	0

Input-output table

Table 3: Input-output matrix, current prices, $t = 8$ (baseline)

	Manuf.	Agric.	Serv.	Recyc.	Total	Fin. dem.	Tot. output
Manufacturing (production)	67.67	67.66	67.69	0	203.02	248.14	451.16
Agriculture (production)	67.68	67.66	67.69	0	203.03	248.04	451.06
Services (provision)	67.67	67.66	67.69	0	203.02	248.24	451.26
Recycling (production)	0.00	0.00	0.00	0	0.00	0	0
Value added	236.32	236.27	236.37	0	708.97		
~ Disposable income	191.22	191.18	191.26	0	573.65		
~ Tax revenue	47.66	47.65	47.67	0	142.97		
~ Interest payments (-)	-2.55	-2.55	-2.55	0	-7.65		
Import (production)	11.82	11.82	11.82	0	35.45	-35.45	
Total output	451.16	451.06	451.26	0	1353.49	708.97	1353.49

Exteded input-output table

Table 4: Extended IO matrix, $t = 8$ (baseline)

	Manufacturing	Agriculture	Services	Recycling	Total
Disposable labour income	85.94	85.92	85.96	0	257.81
Disposable capital income	105.28	105.26	105.30	0	315.84
Functional income inequality	0.18	0.18	0.18	0	0.18
Total employment	537.10	536.97	537.22	0	1611.30
~ Male employment	268.55	268.49	268.61	0	805.65
~ Female employment	268.55	268.49	268.61	0	805.65
Share of female employment	0.50	0.50	0.50	0	0.50
Waste production	220.97	220.94	221.00	0	662.91
Annual emissions of CO2	21.05	21.05	21.06	0	63.16

The circular economy (CE)

- CE = policies that aim at reusing, repairing, sharing, and recycling products and resources to create a closed-loop system, thus minimising waste, pollution, and CO_2 emissions

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- Consider a 4-industry economy: 3 goods + waste. If waste is not recycled, the matrix of technical coefficients is:

$$\mathbf{A} = \begin{pmatrix} a_{11} & a_{12} & a_{13} & 0 \\ a_{21} & a_{22} & a_{23} & 0 \\ a_{31} & a_{32} & a_{33} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

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

A simple CE innovation

- The new matrix will be:

$$\mathbf{A'} = \begin{pmatrix} a'_{11} \leq a_{11} & a'_{12} \leq a_{12} & a'_{13} \leq a_{13} & a'_{14} \geq 0 \\ a'_{21} \leq a_{21} & a'_{22} \leq a_{22} & a'_{23} \leq a_{23} & a'_{24} \geq 0 \\ a'_{31} \leq a_{31} & a'_{32} \leq a_{32} & a'_{33} \leq a_{33} & a'_{34} \geq 0 \\ a'_{41} \geq 0 & a'_{42} \geq 0 & a'_{43} \geq 0 & 0 \end{pmatrix}$$

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

The role of the government sector

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

$$a_{ij} = a_{ij,-1} + \gamma_A \cdot (a'_{ij,-1} - a_{ij,-1}) \tag{28}$$

The role of the government sector

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

Figure 5. CE-oriented government spending

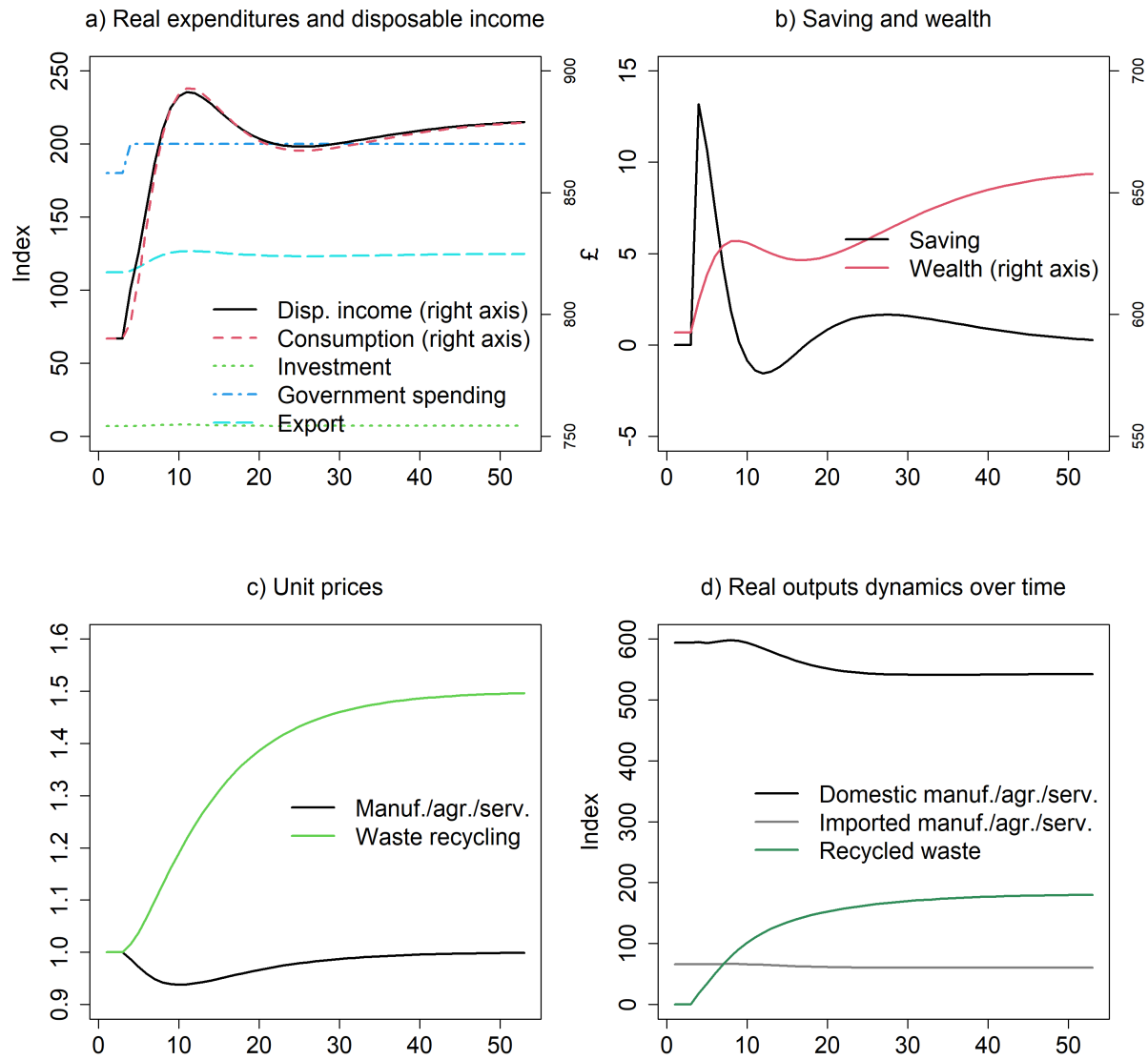


Figure 6. CE-oriented government spending (cont'd)

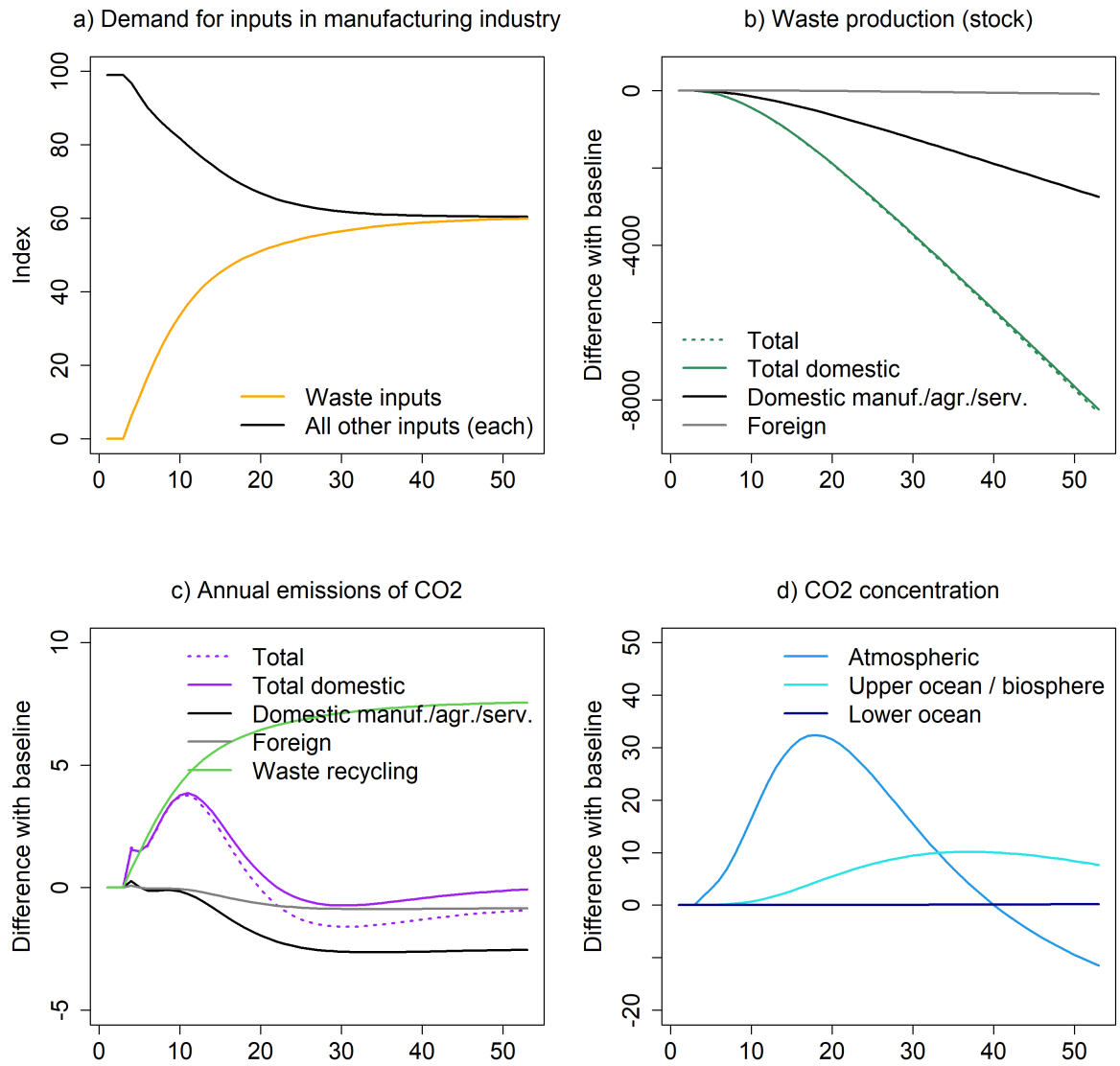


Figure 6B. Using tech. coefficients for Denmark (-10%)...

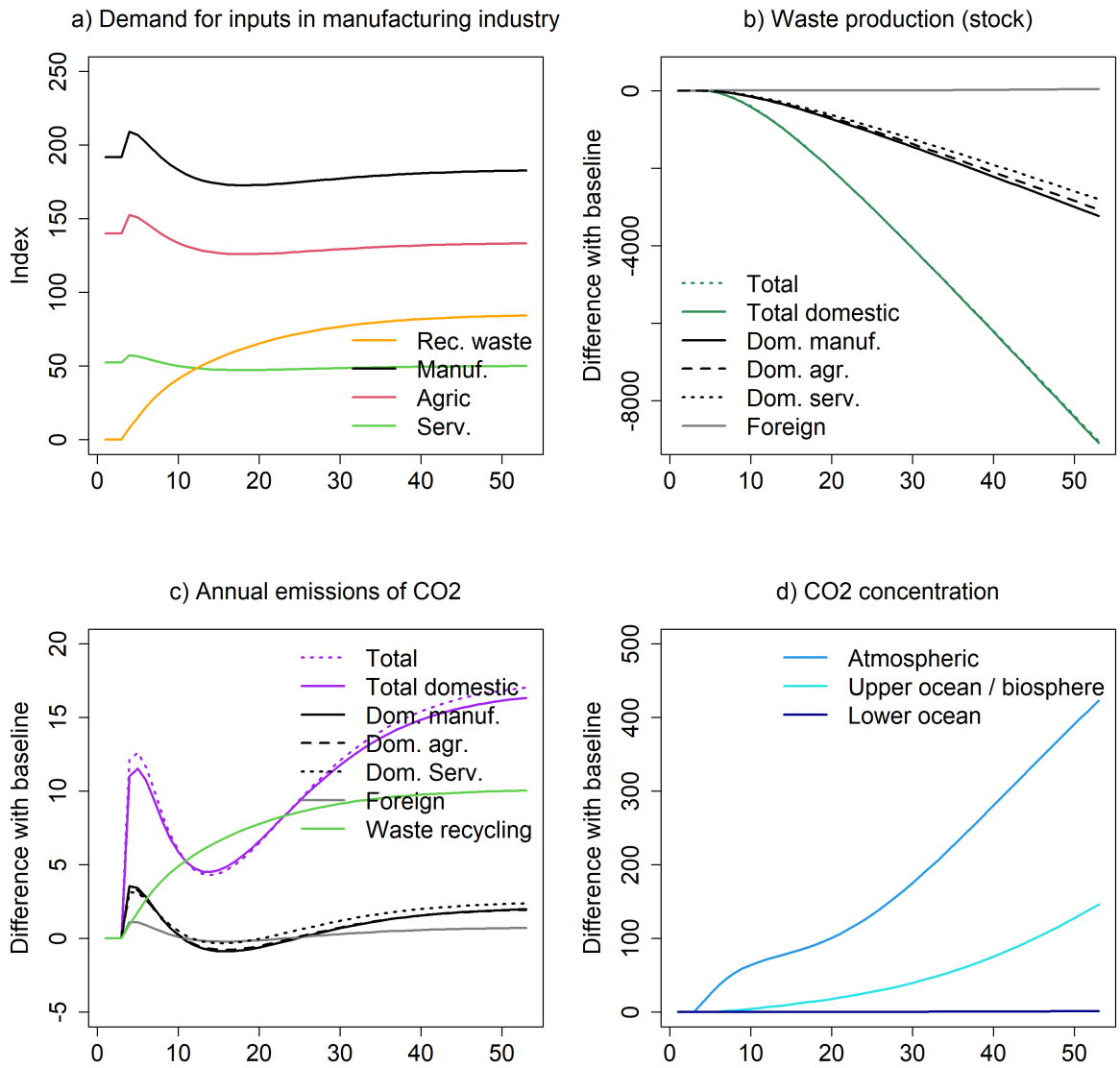
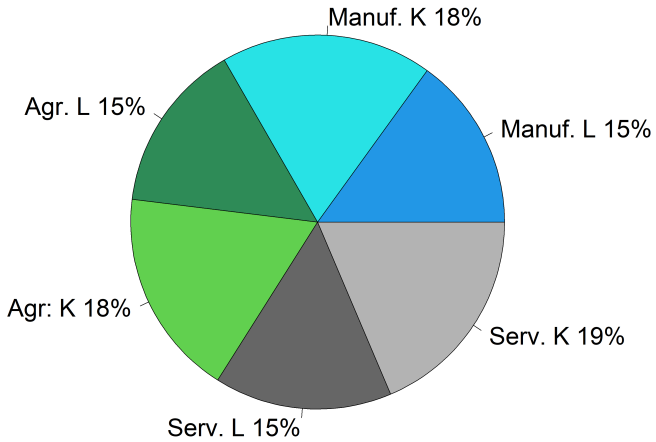
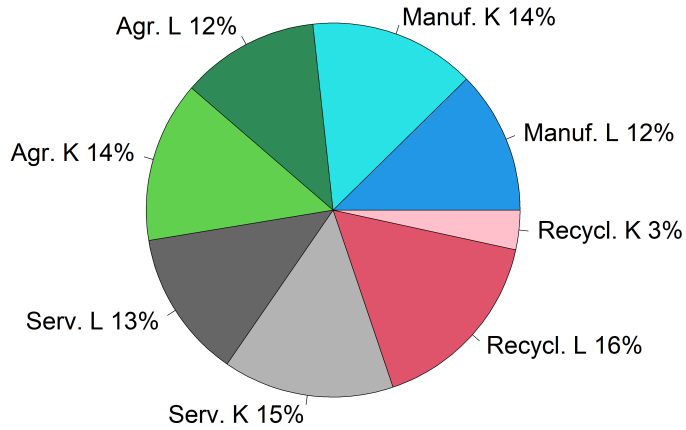


Figure 7. Income distribution and gender segregation

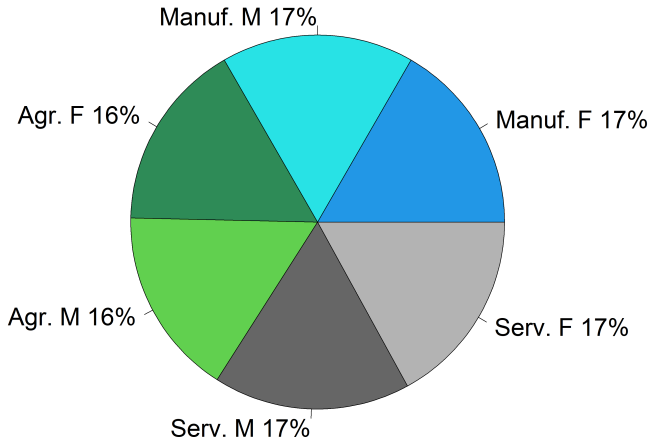
a.1) Income distribution: baseline



a.2) Income distribution: CE innovation



b.1) Gender segregation: baseline



b.2) Gender segregation: CE innovation

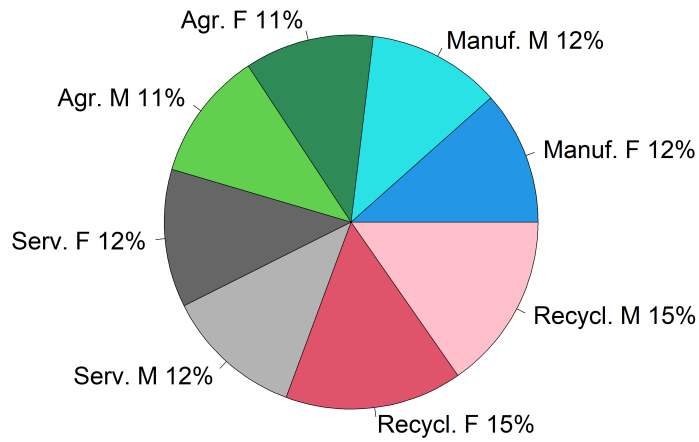


Figure 8. Gender segregation over time

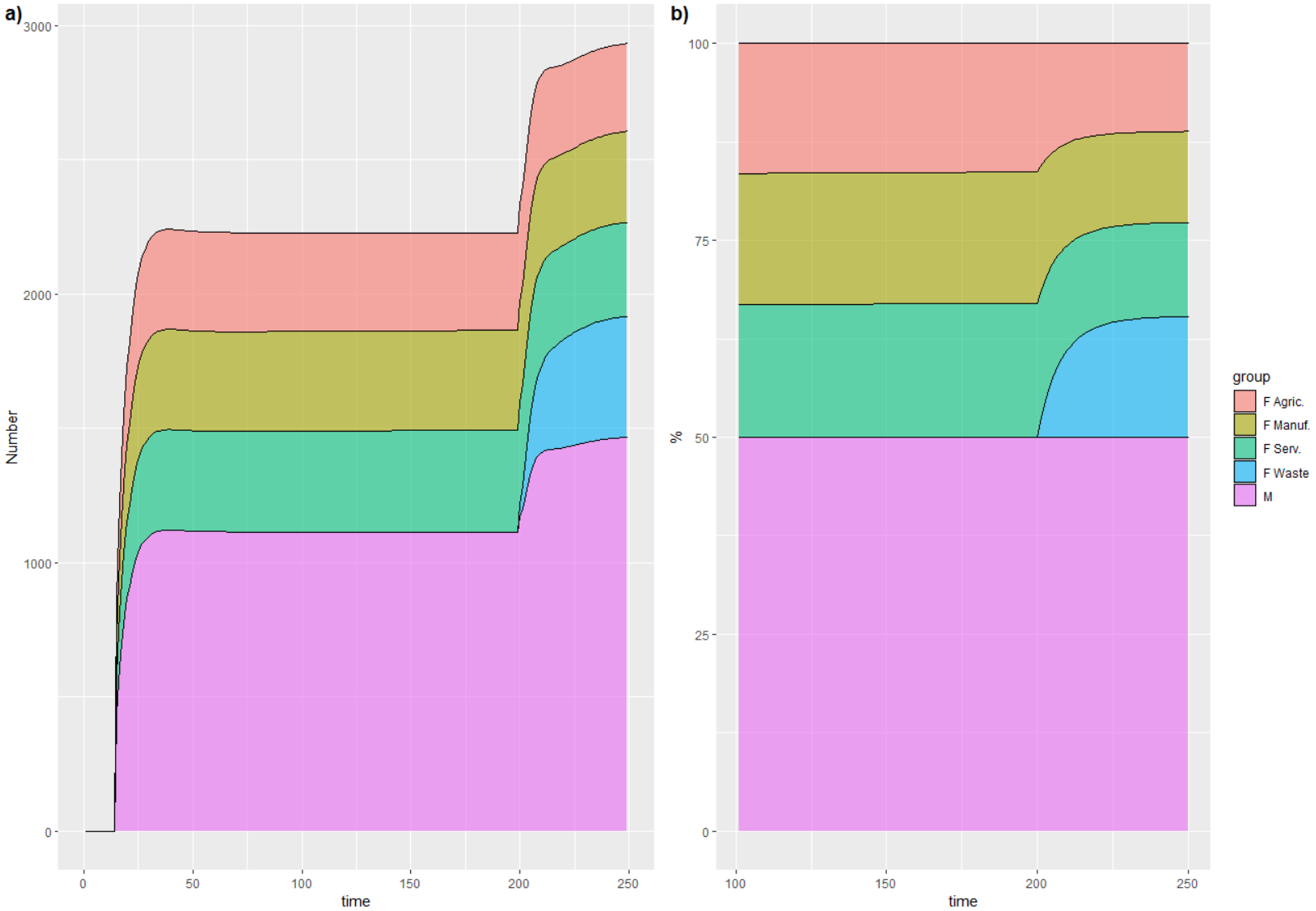
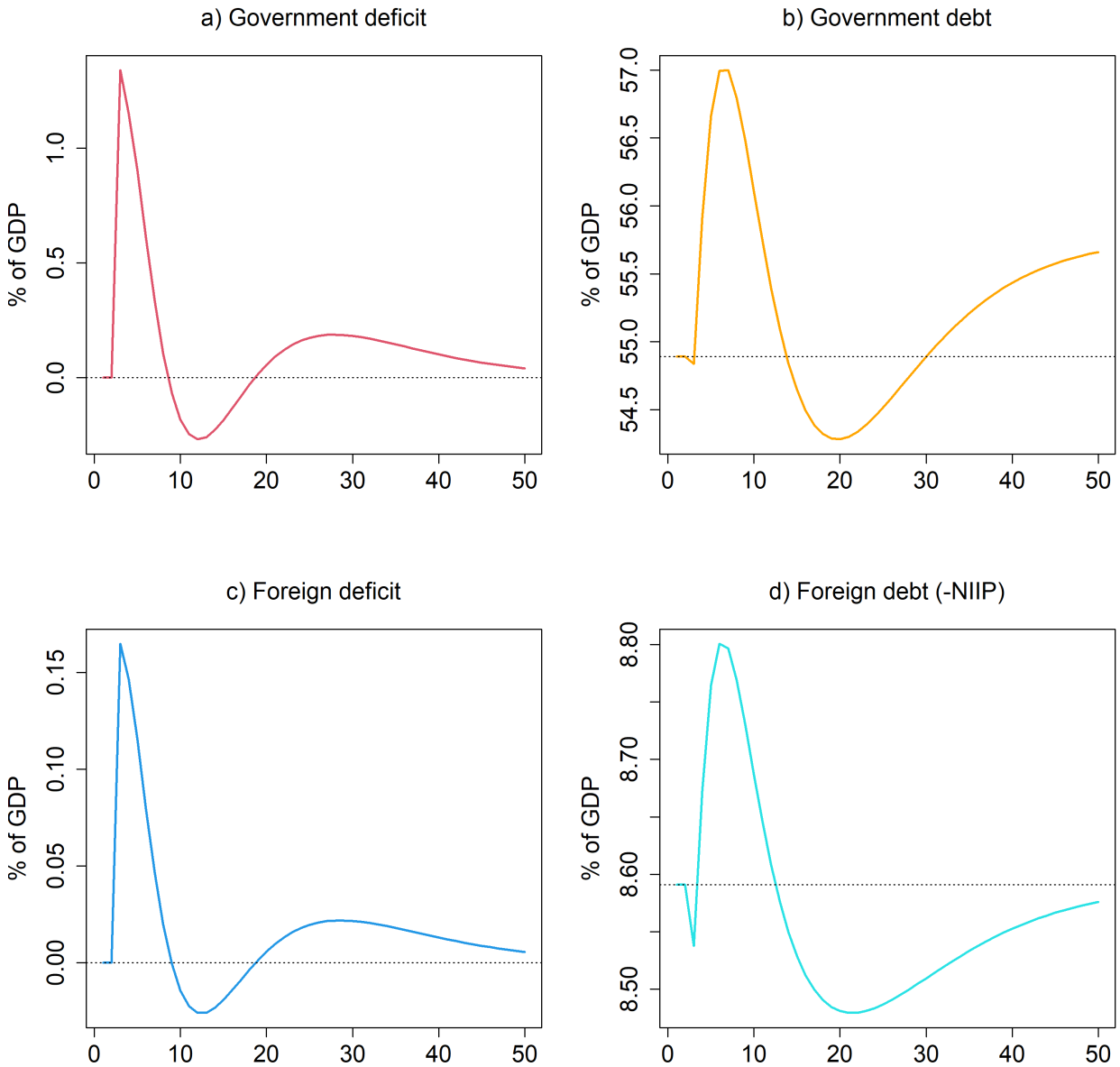


Figure 9. Government and foreign balances



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  g) Improve solver / perform stability analysis

Thank you

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