Circular economy innovations in an input-output stock-flow consistent dynamic model

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November 4, 2022

Abstract

The aim of this paper is twofold. First, a simple input-output stock-flow consistent dynamic model is developed from scratch, in which money is endogenously created, prices are defined in a Sraffa-like fashion, and the economy is split into different industries. Second, the model is used to test the impact of a "circular economy" innovation on output, employment, income inequality, waste, and CO_2 emissions.

Keywords: Stock-Flow Consistent Models, Input-Output Analysis, Circular Economy

JEL Classification: E16, E17, C67, D57

Contents

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1 Introduction

While dynamic stochastic general equilibrium (DSGE) models have dominated macroeconomics since the mid-1990s, seldom have these models been used to deal with environmental topics. This is no surprise, as the small size of DSGE models and their "harmonic oscillator"-like dynamics make them unfit for analyzing climate change-related issues – let alone biodiversity loss, rebound effects, lock-in effects, commons management, circular economy policies, etc. Standard neoclassical growth models (NG) are also unsuitable, as environmental variables do not affect the structural determinants of economic growth (Rivera et al. 2018[6]). As a result, two additional classes of models are usually employed by mainstream economists to address environmental questions: *a*) integrated assessment models (IAM); and *b*) computational general equilibrium models (CGE).

IAMs are specifically designed to integrate the economy with the biosphere and atmosphere. They are usually made up of a number of social, economic, and environmental "modules", which allow quantifying climate-change mitigation scenarios (process-based IAMs) or calculating the social cost of carbon (cost-benefit IAMs). Popular though they are, most IAMs (particularly, cost-benefit IAMs) share the same controversial presuppositions of DSGE and NG models: there is a unique and stable socially-optimal equilibrium in the long run; and the process of adjustment is driven by the decisions made by a hyper-rational representative individual agent who maximizes an intertemporal utility function subject to economic, technical, and/or environmental constraints. Turning to standard CGE models, these are large scale models whose accounting structure is based on input-output tables and the national accounts. As such, they are well-equipped to factor in a variety of social, economic, and environmental variables. Unfortunately, CGE behavioral equations are also based on neoclassical general equilibrium principles.[1] Besides, these models can only compare the economy before and after a shock, thus neglecting the transition from one state to the other.

Is there an alternative? The answer is yes, there is. In fact, there are two: *a*) non-neoclassical or demand-driven input-output models (IO); and *a*) stock-flow consistent macroeconomic models (SFC). IO and SFC models are convenient tools to address environmental issues, as they do not imply any unreasonable behavioral assumptions or any *a priori* equilibrium dynamics. More precisely, IO models shed light on interdependencies across industries and, like standard CGE models, can be easily extended to include ecosystem-related variables. Their main limitation is that are not strictly-defined "dynamic models", as they only compare two different states of the world, thus ignoring the transition between them. SFC models can be regarded as a specific class of system dynamics tools, mostly developed by post-Keynesian macroeconomists since the early 2000s. SFC models have gained momentum in ecological macroeconomics in the last decade, because they allow for a consistent and comprehensive integration of the flows and the stocks of the economy and the ecosystem (e.g. Carnevali et al. 2019[3]). This feature makes them one of the most flexible and versatile tools to simulate, analyse, and compare alternative environmental policy scenarios. Their main limitation is that they only consider aggregate output, so neglecting the interdependencies between different industries.

The aim of this paper is twofold. First, it shows how a basic input-output stock-flow consistent (IO-SFC) model can be developed, thus addressing the main limitations of each class of models taken separately. More precisely, a standard aggregative SFC model (based on Godley and Lavoie 2007, chapters 3-10[5]) is turned into a *meso-founded* model in which both *fiat* money and bank money are endogenously created, market prices adjust to Sraffa-like reproduction prices, and the economy is disaggregated both *vertically* (social sectors) and *horizontally* (production industries). Second, the model is used to assess the impact of a "circular economy" innovation on selected economic, social, and environmental variables.

[1] Some CGE models depart from the standard assumptions of flexible prices and full employment by introducing market frictions. However, their core dynamics is still that of a general equilibrium model.

2 The formal model

The artificial economy economy considered is made up of six macroeconomic sectors: *a*) households (which are then split into wage-earners and rentiers); *b*) private production firms; *c*) the government sector; *d*) commercial banks; *e*) the central bank; and *f*) the foreign sector. Sectors (*a*) to (*e*) are located in the "home" country, whereas (*f*) records the trade and financial flows from/to the rest of the world.

Households are the final recipients of both labour incomes (wages) and capital incomes (profits and interest payments). They buy consumption goods based on both their disposable income and their stock of net wealth. Household savings are made up of cash (currency), bank deposits, and government bills. There are three industries (manufacturing, agriculture, and services, respectively) under the baseline scenario, in which firms produce three outputs (and waste) by means of the same products used as inputs. The foreign sector produces (manufacturing and agricultural) goods and services that are sold to the home country. The related revenues are spent for consumption or saved in the form of home government bills.

For the sake of simplicity, real supplies always adjust to real demands. As a result, firms hold no inventories. However, firms accumulate fixed capital and finance their production plans using bank loans. As mentioned, corporate incomes are entirely distributed to households. Bank deposits are created as long as banks grant loans to firms and/or on demand. Cash is issued by the central bank as the government sector runs into budget deficits and/or commercial banks obtain advances.

2.1 Domestic households

Let's start by defining households' total consumption in real terms, which is:

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

where p_A is a consumer price index, while α_1, α_2 and α_3 are the propensities to consume out of disposable labour income (YD^w), disposable capital income (YD^c) and net wealth (V), respectively.[2]

Disposable income is net domestic incomes from firms and banks *plus* received interest payments on bank deposits and government debt *minus* taxes:

$$\begin{aligned} YD &= WB + F_f + F_b + r_{m,-1} \cdot M_{h,-1} + r_{b,-1} \cdot B_{h,-1} - T = \\ &= (Y_h^n - r_{l,-1} \cdot L_{f,-1} - AF) + F_b + r_{m,-1} \cdot M_{h,-1} + r_{b,-1} \cdot B_{h,-1} - T \end{aligned} \tag{2}$$

where WB is the wage bill, F_f is corporate profit, F_b is bank profit, r_m is the interest rate on deposits held by the households (M_h), r_b is the interest rate on government bills held by the households (B_h), T is the amount of tax payments, Y_h^n is net domestic income, r_l is the interest rate on loans obtained by the firms (L_f), and AF are corporate profits retained in the form of amortization funds.

Net private wealth is:

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

The stock of wealth increases as households save. Portfolio decisions (that is, the way in which net wealth is held) are discussed in the subsection 2.9.

[2] Purely adaptive price expectations are assumed, so that: $E(p_A) = p_{A,-1}$. Besides, the impact of the so-called "inflation tax" on real disposable income is ignored, because prices can only change following a change in technical coefficients.

2.2 Production firms (current)

For each product, the final demand faced by production firms is made up of household consumption, corporate investment in fixed capital, government spending, and export:

$$\begin{aligned}\mathbf{d} = \begin{pmatrix} d_1 \\ d_2 \\ d_3 \end{pmatrix} &= \beta \cdot c + \iota \cdot i_d + \sigma \cdot gov + \eta \cdot exp = \\ &= \begin{pmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \end{pmatrix} \cdot c + \begin{pmatrix} \iota_1 \\ \iota_2 \\ \iota_3 \end{pmatrix} \cdot i_d + \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \end{pmatrix} \cdot gov + \begin{pmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \end{pmatrix} \cdot exp\end{aligned} \tag{4}$$

where i_d is corporate demand for investment (in fixed capital), gov is total government consumption, exp is gross export, β is the vector of household consumption shares (with: $\beta_3 = 1 - \beta_1 - \beta_2$), ι is the vector of investment shares (with: $\iota_3 = 1 - \iota_1 - \iota_2$), σ is the vector of government spending shares (with: $\sigma_3 = 1 - \sigma_1 - \sigma_2$), and η is the vector of export shares (with: $\eta_3 = 1 - \eta_1 - \eta_2$).

The gross output vector is therefore:

$$\mathbf{x} = \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} = \mathbf{A} \cdot \mathbf{x} + \mathbf{d}$$

from which:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{d} \tag{5}$$

where $\mathbf{I}$ is the identity matrix and $\mathbf{A}$ is the matrix of technical coefficients, defined as:

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

As usual, a_{ij} (with $i, j = 1, 2, 3$) is the quantity of product i necessary to produce one unit of product j. Therefore, each column j of $\mathbf{A}$ is associated with an industry, a the technique of production, and a product. Notice that the term $(\mathbf{I} - \mathbf{A})^{-1}$ is a matrix too. It is named the *Leontief inverse* and shows the multipliers, that is, the successive changes in production processes triggered by an initial change in final demands.[3]

The monetary value of gross output for the whole economy is the product of the unit price vector and the output vector:

$$Y = \mathbf{p}^T \cdot \mathbf{x} \tag{6}$$

where $\mathbf{p}$ is the price vector and the subscript "T" stands for the transpose of the matrix (hence $\mathbf{p}^T$ is a row vector).

The monetary value of gross domestic output (for the home country) is:

$$Y_h = Y - \mathbf{p}^T \cdot \mathbf{x}_{fo} \tag{7}$$

where $\mathbf{x}_{fo}$ is the vector of outputs produced by the foreign sectors.

The net income or value added for the whole economy is:

$$Y^n = \mathbf{p}^T \cdot \mathbf{d} \tag{8}$$

[3] As is well known, the Leontief inverse matrix can be expressed as a sum of power series (Waugh 1950[8]), that is: $(\mathbf{I} - \mathbf{A})^{-1} = \mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \ ... \ + \mathbf{A}^t + \ ... \ = \sum_{t=0}^{\infty} \mathbf{A}^t$.

The net domestic income (for the home country) is:

$$Y_h^n = Y^n - \mathbf{p}^T \cdot (\mathbf{m} \odot \mathbf{d}) \tag{9}$$

where m is the vector of import shares to total demands for goods and services, and $\odot$ is the Hadamard product.[4]

Using the subscript j to denote industries ($j = 1 =$ manufacturing; $j = 2 =$ agriculture; $j = 3 =$ services), the value added in each of them is:

$$VA_j = x_j \cdot p_j - \sum_{i=1}^{3} (x_j \cdot a_{ij} \cdot p_i) - m_j \cdot d_j \cdot p_j \tag{10}$$

$\forall j = 1, 2, 3$. Notice that total value added by domestic productions matches net domestic income, that is, $VA_1 + VA_2 + VA_3 = Y_h^n$.

Finally, corporate profit is:

$$F_f = Y_n^n - WB - r_{l,-1} \cdot L_{f,-1} - AF \tag{11}$$

The latter is entirely distributed (to the household sector).

2.3 Production firms (capital)

Firms need fixed capital (in addition to labour and circulating capital inputs) to produce. It is assumed that each industry has its own capital requirement. The target stock of fixed capital, expressed in real terms, is therefore:

$$k^* = \frac{\mathbf{p}_{-1}^T \cdot (\mathbf{h} \odot \mathbf{x}_{-1})}{p_{I,-1}} \tag{12}$$

where $\mathbf{h} = \{h_j\}$ is the column vector of industry-specific target capital to output ratios, and p_I is the average price of investment goods.[5]

The real gross investment adjusts in such a way to bridge the gap between the actual capital stock (at the beginning of the period) and its target level:

$$i_d = \gamma \cdot (k^* - k_{-1}) + da \tag{13}$$

where γ defines the speed of adjustment, and da is capital depreciation.

The current capital stock depreciates according to a constant ratio, δ, so that:

$$da = \delta \cdot k \tag{14}$$

It follows that the real stock of current fixed capital is:

$$k = k_{-1} + i_d - da \tag{15}$$

Firms retain a portion of their profits as amortization funds, which are used to fund the replacement of depleted capital:

$$AF = da \cdot p_I \tag{16}$$

The stock of bank loans obtained by production firms is defined as a residual variable:

$$L_f = L_{f,-1} + i_d \cdot p_I - AF \tag{17}$$

At the end of each period, new bank loans equal the investment in fixed capital that has not been funded using internal resources (amortization funds).

[4] Also named element-wise multiplication of matrices.

[5] Notice that k^* cannot be expressed in physical units. Rather, it is calculated by dividing the nominal stock of capital by the average price of investment goods. See subsection 2.8.

2.4 Commercial banks

For the sake of simplicity, it is assumed that banks are always available to finance the production and investment plans of private firms. Supplied loans are therefore:

$$L_s = L_{s,-1} + \Delta L_f \tag{18}$$

Banks provide deposits on demand:

$$M_s = M_h \tag{19}$$

Because of cash (or state money), deposits collected by the banks may exceed those created by granting loans to the firms. If this happen, banks hold government bills as the asset counterpart of extra-deposits. By contrast, if loans exceed deposits, banks request (and obtain) advances from the central bank:

$$if\ M_s \geq L_s\ then\ B_b = M_s - L_s\ and\ A_d = 0 \tag{20}$$

$$if\ M_s < L_s\ then\ B_b = 0\ and\ A_d = L_s - M_s \tag{21}$$

where A_d are advances obtained by commercial banks from the central bank.

It is assumed that the interest rate on advances is nil, banks have no costs of production, and there are no compulsory reserves. As a result, bank profits equal the difference between perceived interests on loans and bills and interest payments on deposits:

$$F_b = r_l \cdot L_s + r_b \cdot B_b - r_m \cdot M_s \tag{22}$$

Like corporate profits, bank profits are entirely distributed to the households.[6]

2.5 Government and central bank

Government spending grows according to an exogenous rate:[7]

$$gov = gov_{-1} \cdot (1 + g_g) + gov_0 \tag{23}$$

where g_g is the growth rate of government spending and gov_0 is a shock component.

Taxes collected by the government can be calculated using the average tax rate on households' total income. The total tax revenue is therefore:

$$T = \theta \cdot (Y_h^n + r_{m,-1} \cdot M_{h,-1} + r_{b,-1} \cdot B_{h,-1}) \tag{24}$$

where θ is the tax rate on income and B_h is the stock of bills held by the households.

The government budget deficit is:

$$DEF_g = gov \cdot p_G - T + r_b \cdot (B_h + B_b + B_{fo}) \tag{25}$$

The government sector issues bills as it runs into deficits:

$$B_s = B_{s,-1} + DEF_g \tag{26}$$

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

$$B_{cb} = B_s - B_h - B_b - B_{fo} \tag{27}$$

Advances to commercial banks are provided on demand:

$$A_s = A_d \tag{28}$$

Consequently, cash is created as the central bank buys the bills that are not held by the private sector and/or provides advances to commercial banks:

$$H_s = H_{s,-1} + (B_{cb} - B_{cb,-1}) + (A_s - A_{s,-1}) \tag{29}$$

This is the overall amount of state money that remains in circulation at the end of each period.

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[6] Clearly, if one assumes that $r_l = r_b = r_m$, then $F_b = 0$.

[7] However, it is assumed that $g_g = 0$ in the baseline scenario – see Table 5.

2.6 Foreign sector

For the sake of simplicity, all foreign variables are expressed in home currency. Like domestic consumption, real export is modeled based on a stock-flow norm:

$$exp = \alpha_4 \cdot \frac{YD_{fo}}{E(p_{fo})} + \alpha_5 \cdot \frac{V_{fo,-1}}{p_{fo,-1}} \tag{30}$$

where α_4 and α_5 are the propensities to import (consume) of foreign economic agents out of their disposable income (YD_{fo}) and net wealth (V_{fo}), respectively.[8]

Foreign industries use the same technologies of home industries to produce agricultural and manufacturing goods that are entirely shipped abroad, and services for the home country. The final demand (of the home economy) for imported goods and services can be defined as:

$$\mathbf{imp} = \mathbf{m} \odot \mathbf{d} \tag{31}$$

where $\mathbf{m}$ is the vector of industry-specific shares of import on final demands.

However, total production of imported goods is higher than **imp**, as it includes the quantity of them used as inputs:

$$\mathbf{x}_{fo} = \mathbf{m} \odot \mathbf{x} \tag{32}$$

As a result, the gross foreign product, expressed in home currency, is:

$$Y_{fo} = \mathbf{p}^T \cdot \mathbf{x}_{fo} \tag{33}$$

Similarly, the net income of the foreign sector is:

$$Y_{fo}^n = \mathbf{p}^T \cdot \mathbf{imp} \tag{34}$$

Assuming that there are no taxes in the foreign country, their disposable income is:

$$YD_{fo} = Y_{fo}^n + r_b \cdot B_{fo,-1} \tag{35}$$

As a result, the stock of net wealth held by foreign agents is:

$$V_{fo} = V_{fo,-1} + YD_{fo} - p_{fo} \cdot exp \tag{36}$$

For the sake of simplicity, foreign agents are assumed to hold all their net wealth (which they accumulate by shipping goods and selling services to the home country) in the form of home government bills:

$$B_{fo} = V_{fo} \tag{37}$$

Because of this assumption, the exchange rate can never change.

2.7 Labour market

The employment level is determined by firms' demand for labour in each production process. More precisely, the number of workers hired in each industry is:

$$N_j = \frac{(x_j - x_{j,fo})}{pr_j} \tag{38}$$

$\forall j = 1, 2, 3$, where pr_j is the product per worker in the j-th industry.

[8] As usual, price expectations are purely adaptive in the model: $E(p_{fo}) = p_{fo,-1}$. Also notice that the impact of the price of home export (foreign import) on foreign consumption, through changes in the real value of the stock of wealth, is neglected.

Total employment, including foreign employment, is:

$$N = \mathbf{x}^T \cdot \left[\begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} \oslash \mathbf{pr} \right] = \mathbf{x}^T \cdot \mathbf{l} \tag{39}$$

where $\oslash$ is the Hadamard division,[9] $\mathbf{pr}$ is the labour productivity vector, and therefore $\mathbf{l}$ is the column vector of labour coefficients.

Domestic employment is:

$$N_h = (\mathbf{x} - \mathbf{x}_{fo})^T \cdot \mathbf{l} = \sum_{j=1}^{3} N_j \tag{40}$$

The wage bill paid in each industry is:

$$WB_j = w \cdot N_j \tag{41}$$

$\forall j = 1, 2, 3$, where w is the uniform money wage rate.

As a result, the total wage bill is:

$$WB = \sum_{j=1}^{3} WB_j \tag{42}$$

The equation above defines the overall cost of labour faced by private firms in the home economy.

2.8 Price setting

Private firms use a markup rule. More precisely, they set industry-specific costing margins over their unit costs of production. The vector of unit prices of reproduction is:

$$\mathbf{p}^* = w \cdot \mathbf{l} + \mathbf{p}^* \cdot \mathbf{A} \odot \mathbf{m}^* \tag{43}$$

where $\mathbf{m}^* = \{1 + \mu_j^*\}$ is the vector of normal mark-ups, from which one obtains:

$$\mathbf{p}^* = \begin{pmatrix} p_1^* \\ p_2^* \\ p_3^* \end{pmatrix} = \begin{pmatrix} \frac{w}{pr_1} + (p_1^* \cdot a_{11} + p_2^* \cdot a_{21} + p_3^* \cdot a_{31}) \cdot (1 + \mu_1^*) \\ \frac{w}{pr_2} + (p_1^* \cdot a_{12} + p_2^* \cdot a_{22} + p_3^* \cdot a_{32}) \cdot (1 + \mu_2^*) \\ \frac{w}{pr_3} + (p_1^* \cdot a_{13} + p_2^* \cdot a_{23} + p_3^* \cdot a_{33}) \cdot (1 + \mu_3^*) \end{pmatrix}$$

Like Sraffa, we assume that "the wage is paid *post factum* as a share of the annual product" (Sraffa 1960, p. 11[7]). However, normal mark-ups are allowed to differ across industries. In other words, there is no tendency for industry-specific profit rates to level out.

In addition, market prices only adjust gradually to reproduction prices:[10]

$$\mathbf{p} = \Gamma \odot \mathbf{p}_{-1} + \left[\begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} - \Gamma \right] \odot \mathbf{p}^* \tag{44}$$

where $\Gamma = \{\gamma_{p_j}\}$ is a vector of coefficients defining the degree of stickiness of market prices.

The average price level faced by the households depends on the basket of goods they consume in each period:

$$p_A = \mathbf{p}^T \cdot \beta \tag{45}$$

[9] Also called element-wise division of matrices.

[10] It follows that actual marks-ups fall below normal mark-ups as long as $p_j < p_j^*$, and they exceed them as long as $p_j > p_j^*$, $\forall j = 1, 2, 3$.

Table 1: Balance sheet in period $t = 20$ (baseline scenario)

	Households	Firms	Government	Banks	CB	Foreign	Total
Money	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

Table 2: Transactions-flow matrix in period $t = 20$ (baseline scenario)

	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 money stock	-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

Table 3: Input-output matrix in period $t = 20$ (baseline scenario)

	Manufacturing	Agriculture	Services	Recycling	Total	Final demand	Total output
Manufacturing (production)	67.67	67.67	67.67	0	203.02	248.14	451.16
Agriculture (production)	67.67	67.67	67.67	0	203.02	248.14	451.16
Services (provision)	67.67	67.67	67.67	0	203.02	248.14	451.16
Recycling (production)	0	0	0	0	0	0	0
Value added	236.32	236.32	236.32	0	708.97		
~ Disposable income	191.22	191.22	191.22	0	573.65		
~ Tax revenue	47.66	47.66	47.66	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	451.16	451.16	0	1353.49	708.97	1353.49

Table 4: Extended IO matrix in period $t = 20$ (baseline scenario)

	Manufacturing	Agriculture	Services	Recycling	Total
Disposable labour income	85.94	85.94	85.94	0	257.81
Disposable capital income	105.28	105.28	105.28	0	315.84
Functional income inequality*	0.18	0.18	0.18	0	0.18
Total employment	537.10	537.10	537.10	0	1611.30
~ Male employment	268.55	268.55	268.55	0	805.65
~ Female employment	268.55	268.55	268.55	0	805.65
Share of female employment	0.50	0.50	0.50	0	0.50
Waste production	220.97	220.97	220.97	0	662.91
Annual emissions of CO2	21.05	21.05	21.05	0	63.16

Similarly, the average price paid by production firms to buy investment goods is:

$$p_I = \mathbf{p}^T \cdot \iota \tag{46}$$

The average price paid by the government is:

$$p_G = \mathbf{p}^T \cdot \sigma \tag{47}$$

Finally, the average price of export is:

$$p_{fo} = \mathbf{p}^T \cdot \eta \tag{48}$$

Notice that these average prices are used to express the components of aggregate demand in real terms, thus avoiding using disaggregated functions for consumption, investment, government spending and export.

2.9 Portfolio choices

Domestic household holdings of government bills are a proportion of their net wealth, which depends positively on the interest rate on government bills, and negatively on both the interest rate on bank deposits and the transactions-led demand for money (approximated by the disposable income to wealth ratio):

$$\frac{B_h}{V} = \lambda_0 - \lambda_1 \cdot r_m + \lambda_2 \cdot r_b - \lambda_3 \cdot \frac{YD}{V} \tag{49}$$

The amount of cash held by the public is a growing function of expected (that is, past) consumption:

$$H_h = \lambda_c \cdot c_{-1} \cdot p_{A,-1} \tag{50}$$

Bank deposits held by the households act as the buffer stock of assets:

$$M_h = V - B_h - H_h \tag{51}$$

It follows that the redundant equation of the model is:

$$H_h = H_s$$

The first term is defined by equation 50, that is, by households' portfolio plans. The second term is defined by equation 29, that is, by the policy makers (central bank and government).

The model is now complete. In the next section, we check the accounting consistency of it, and we assess its dynamic behaviour. A time-span of 100 periods is considered. Model parameters and exogenous variables are shown by Table 5. They have been identified in such a way as to reproduce approximately the baseline scenario discussed by Codina and Fevereiro (2022). Initial values for endogenous variables are all set to zero, unless specified otherwise. Simultaneous solutions for endogenous variables have been found by running 100 iterations per period.[11]

3 Accounting consistency and model extensions

Figure 1 shows that every payment comes from somewhere (a sector) and goes to somewhere (another sector). There are no accounting "black holes" and the model is fully consistent.[12] Figure 1 is the graphical counterpart of Table 2, that is, the transactions-flow matrix of the economy. The corresponding balance sheet is displayed by Table 1. It shows the stocks of financial assets and liabilities associated with each sector.

[11] The model has been developed using *R*. The model code is available at: github.com/marcoverpas.

[12] This implies that: $H_{h,t} - H_{s,t} = 0 \; \forall \; t = 1, 2, ..., 100$ (under any scenarios).

Figure 1: Sankey diagram of cross-sector transactions and changes in stocks in $t = 20$

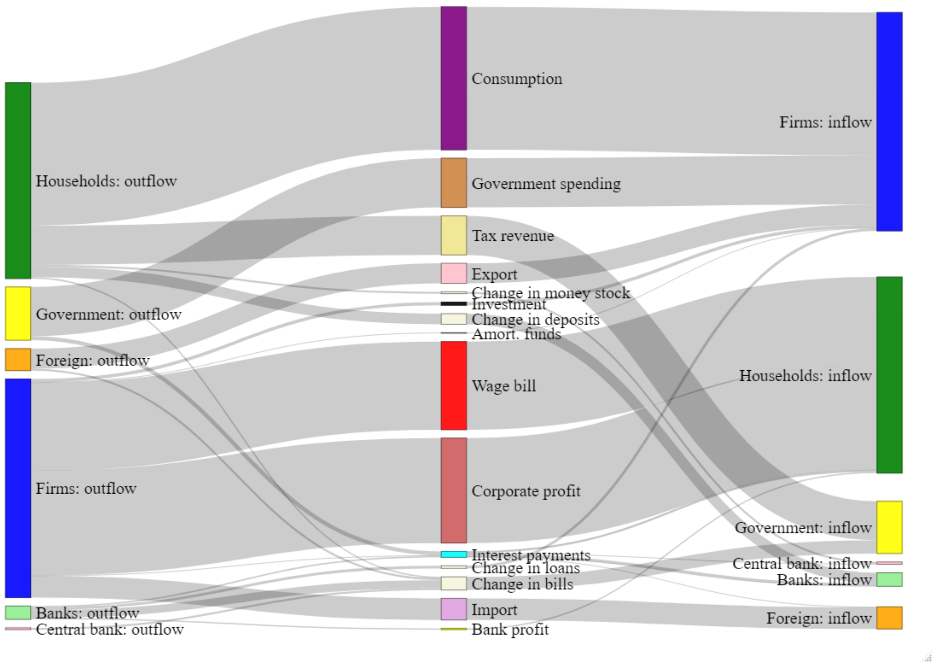
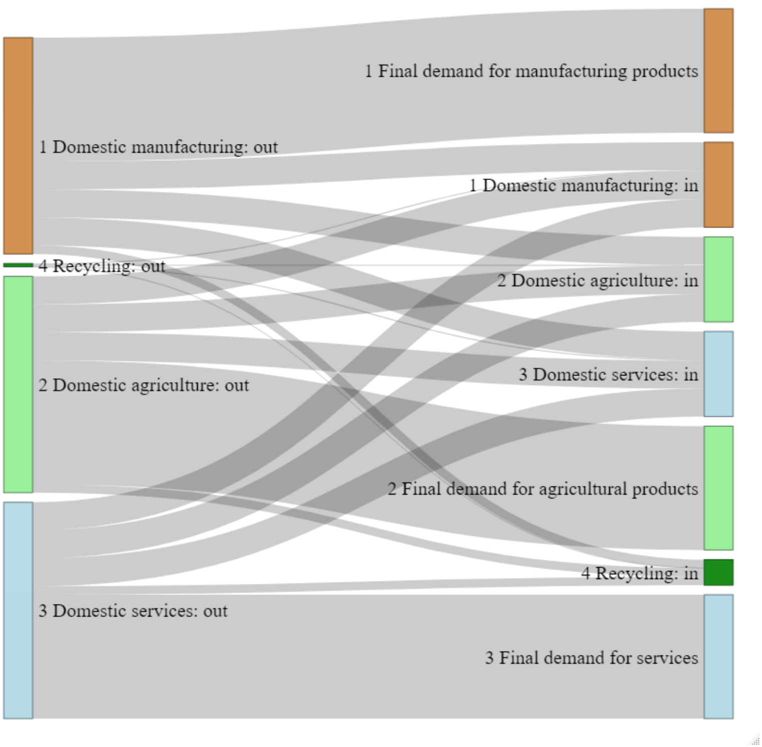


Figure 2: Cross-industry interdependencies: physical flows in $t = 205$ (CE scenario)



What about physical flows? Figure 2 addresses this question by providing a snapshot of cross-industry interdependencies and their relations with final demands for products and services. It can be regarded as the graphical counterpart of Table 3, which shows the input-output structure of the model and the distribution of the value added.

Figure 3 shows how selected variables behave over time in the baseline scenario. The economy is set in motion by an initial expenditure from the government sector ($g_{t=14} = 180$). Private firms produce goods and services on demand. This generates an increase in output, disposable income, consumption, investment, and import (hence export). The economy grows following the initial shock and then stabilises at a new steady-state, where private consumption equals disposable income and the stock of net wealth remains unchanged (so that households achieve their target wealth to income ratio).

Now the model can be further extended to factor in gender divide in the labour market, functional income inequality, and CO_2 emissions. Starting from gender segregation, female employment in each industry can be simply defined as a percentage ρ_j (with $j = 1, 2, 3$, and $\rho_3 = 1 - \rho_1 - \rho_2 \geq 0$) of total workers hired there:

$$N_j^{fem} = \rho_j \cdot N_j \tag{52}$$

Therefore, total female employment in the economy is:

$$N^{fem} = \sum\nolimits_{j=1}^{3} N_j^{fem} \tag{53}$$

Turning to functional distribution, the disposable income in each industry can be simply calculated as:[13]

$$YD_j = YD \cdot \frac{VA_j}{Y_n} \tag{54}$$

$\forall j = 1, 2, 3$. If one assumes that the workers are the only recipients of labour incomes whereas the rentiers (or capitalists) are the only recipients of capital incomes (including corporate profits, bank profits, and interest payments), then the disposable income of the workers in each industry is:

$$YD_j^w = WB_j \cdot (1 - \theta) \tag{55}$$

$\forall j = 1, 2, 3$. Total disposable income of the workers is therefore:

$$YD^w = \sum_{j=3}^{3} YD_j^w \tag{56}$$

Symmetrically, the disposable income of the rentiers in each industry is:[14]

$$YD_j^c = YD_j - YD_j^w \tag{57}$$

$\forall j = 1, 2, 3$, so that their overall disposable income is:

$$YD^c = \sum_{j=1}^{3} YD_j^c \tag{58}$$

Waste accumulates as goods and services are produced. The waste associated with each domestic industry is calculated using the related waste to output ratio, ζ_j, that is:

$$WA_j = WA_{j,-1} + (x_j - x_{j,fo}) \cdot \zeta_j - x_j \cdot a_{4,j} \tag{59}$$

[13] Taxes and interest payments associated with each industry can be determined in the same way.
[14] Notice that, for the sake of simplicity, there is no asset corresponding to firms' ownership in the model.

Figure 3: Selected variables over time

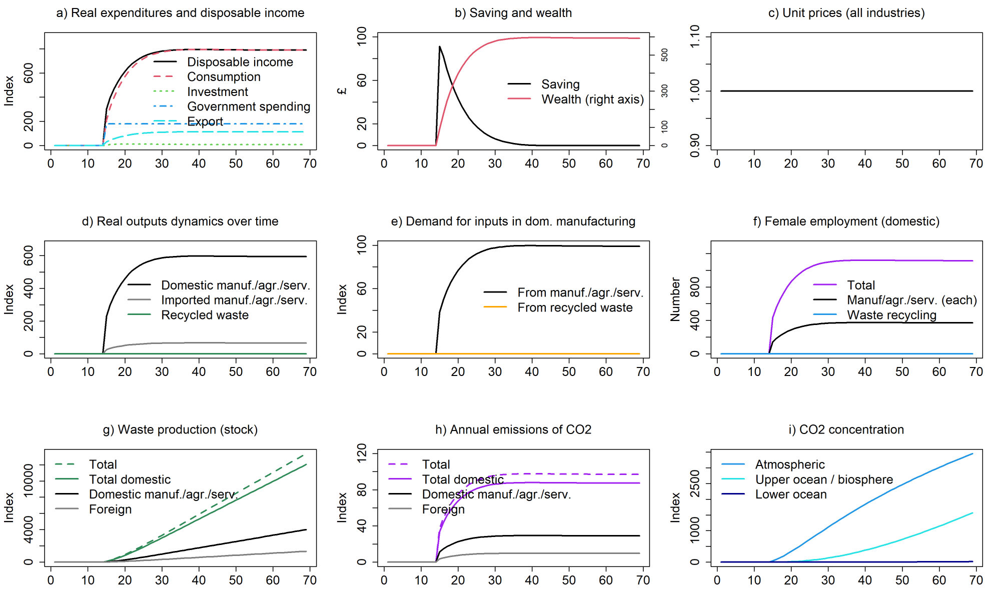
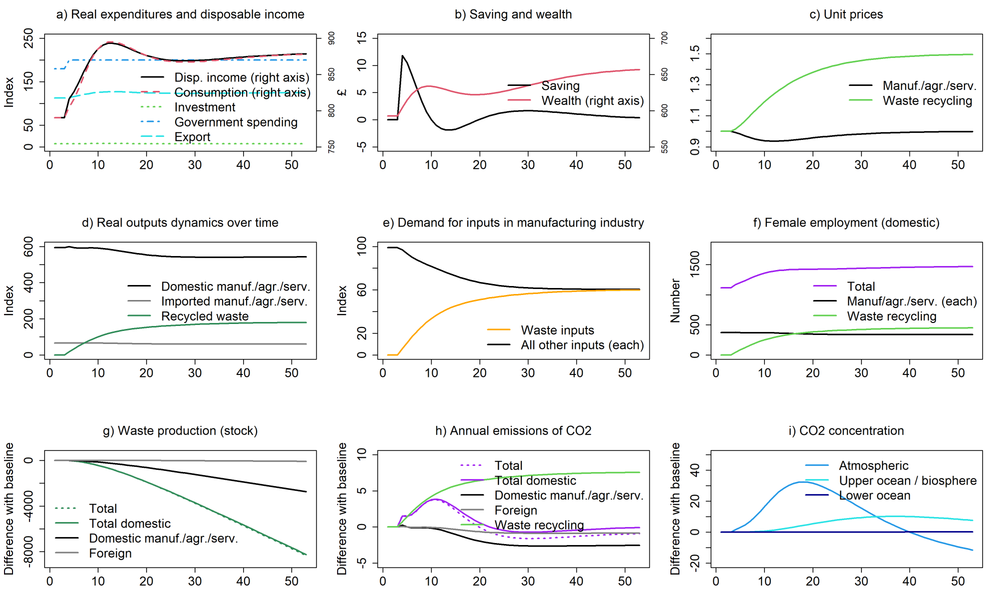


Figure 4: Selected variables after CE in $t = 201$ (starting from $t = 199$)



$\forall j = 1, 2, 3$, where $a_{4,j}$ shows that, in principle, waste can be reduced by recycling it and using is as an input for the other industries. This point is discussed further in Section 4.

Similarly, the waste produced by foreign industries is:

$$WA_{fo} = WA_{fo,-1} + \sum_{j=1}^{3} (x_{j,fo} \cdot \zeta_{j,fo}) \tag{60}$$

Total domestic waste is therefore:

$$WA = \sum_{j=1}^{3} WA_j \tag{61}$$

If one assumes away renewable energy sources and land emissions, annual emissions of CO_2 can be calculated for each industry by multiplying their respective output by the industry-specific energy intensity coefficient ($\varepsilon_j = Ej_j/x_j$) and then by a common CO_2 intensity coefficient ($\beta_e = Gt/Ej$). Emissions linked with each domestic industry are:

$$EM_j = (x_j - x_{j,fo}) \cdot \varepsilon_j \cdot \beta_e \tag{62}$$

$\forall j = 1, 2, 3$, whereas emissions associated with foreign industries are:

$$EM_{fo} = \beta_e \cdot \sum_{j=1}^{3} (x_{j,fo} \cdot \varepsilon_{j,fo}) \tag{63}$$

Therefore, total domestic emissions per year are:

$$EM = \sum_{j=1}^{3} EM_j \tag{64}$$

The carbon cycle is defined by the interaction of atmospheric CO_2 concentration, upper-ocean/biosphere CO_2 concentration, and lower-ocean CO_2 concentration. Foreign emissions must be included too:

$$CO_2^{AT} = EM + EM_{fo} + \phi_{11} \cdot CO_{2,-1}^{AT} + \phi_{21} \cdot CO_{2,-1}^{UP} \tag{65}$$

$$CO_2^{UP} = \phi_{12} \cdot CO_{2,-1}^{AT} + \phi_{22} \cdot CO_{2,-1}^{UP} + \phi_{32} \cdot CO_{2,-1}^{LO} \tag{66}$$

$$CO_2^{LO} = \phi_{23} \cdot CO_{2,-1}^{UP} + \phi_{33} \cdot CO_{2,-1}^{LO} \tag{67}$$

where ϕ_{ji} (with $j = i = 1, 2, 3$) are defined exogenously.

The adjustment of female employment, waste production, CO_2 annual emissions, and CO_2 concentration to their respective steady-state values, following the initial shock to government spending, is shown by Figure 3. A summary of the numerical values of selected variables is provided by Table 4, in which an income inequality index and a gender segregation index are also calculated for each industry and the economy as a whole.[15]

4 Introducing a circular economy innovation

The label "circular economy" (CE) denotes a set of policies and practices that aim at reusing, repairing, sharing, and recycling products and resources to create a closed-loop system, thus minimizing waste, pollution and CO_2 emissions.[16] A simple way to introduce a CE innovation in the model above is to consider a 4-industry economy, in which the first three industries produce goods and services, whereas the fourth industry deals with waste recycling.

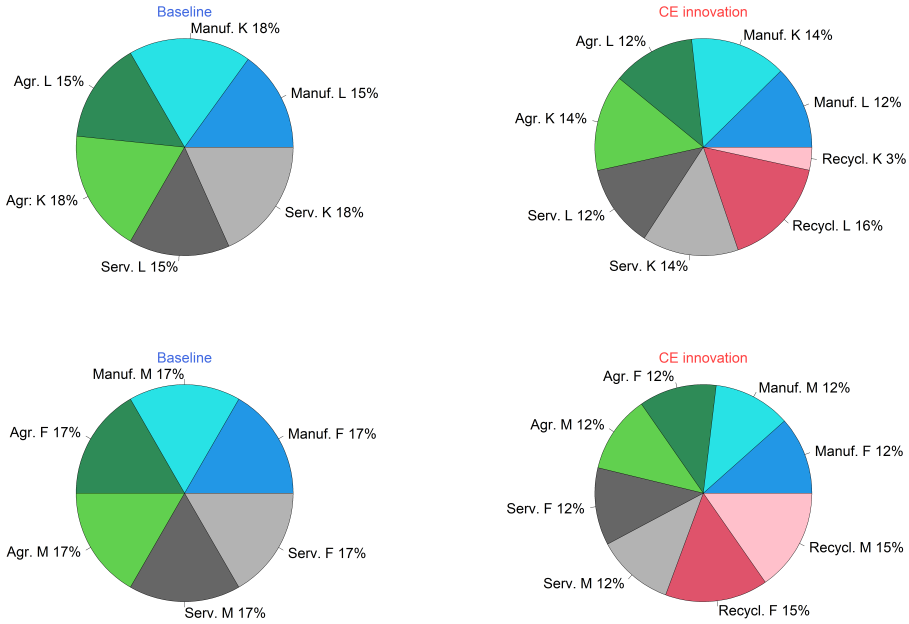
As long as waste is not recycled, the matrix of technical coefficients is:

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

[15] Functional inequality is: $\chi_y = \left| 1 - \frac{YD_j^w}{YD_j^c} \right|$; gender segregation is: $\chi_{fem} = \frac{N_j^{fem}}{N_j}$, $\forall j = 1, 2, 3$.

[16] For a thorough discussion on the definition of CE, see Bimpizas-Pinis et al. 2021.[1]

Figure 5: Income distribution and gender segregation after CE



All industries generate waste, but no waste is used as input ($a_{41} = a_{42} = a_{43} = 0$) and no inputs are used in the waste industry ($a_{14} = a_{24} = a_{34} = 0$).

In this simplified model, a CE innovation implies a change in technical coefficients such that the new matrix is:

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

In short, the CE innovation entails a reduction in the quantities of (manufacturing and agricultural) products and services used as inputs in the same industries (green coefficients). This is possible because recycled waste now enters their production processes (red coefficients).[17] Besides, manufacturing and agricultural products, and services, will be used as inputs in the waste recycling industry (blue coefficients).

The unit price of recycled waste now enters equation 43 in subsection 2.8. It is defined in the same way as the other prices. The mark-up applied by the recycling industry is set using the average mark-up of the economy:

$$\mu_4 = \mu_{4,-1} + \gamma_\mu \cdot (\bar{\mu} - \mu_{4,-1}), \quad with : \bar{\mu} = \frac{\sum_{j=1}^{3} \mu_j}{3} \tag{68}$$

where γ_μ is the speed of convergence of the initial mark-up value (0, in the simulations below) to the average one.

[17] As CE innovation seems to imply some degree of input substitutability, one might notice that *smooth substitutability*, within the *same production function*, is one of the key assumptions of neoclassical general equilibrium models. However, input substitution is only possible here because of a *change in the techniques of production*.

Figure 6: Gender segregation over time

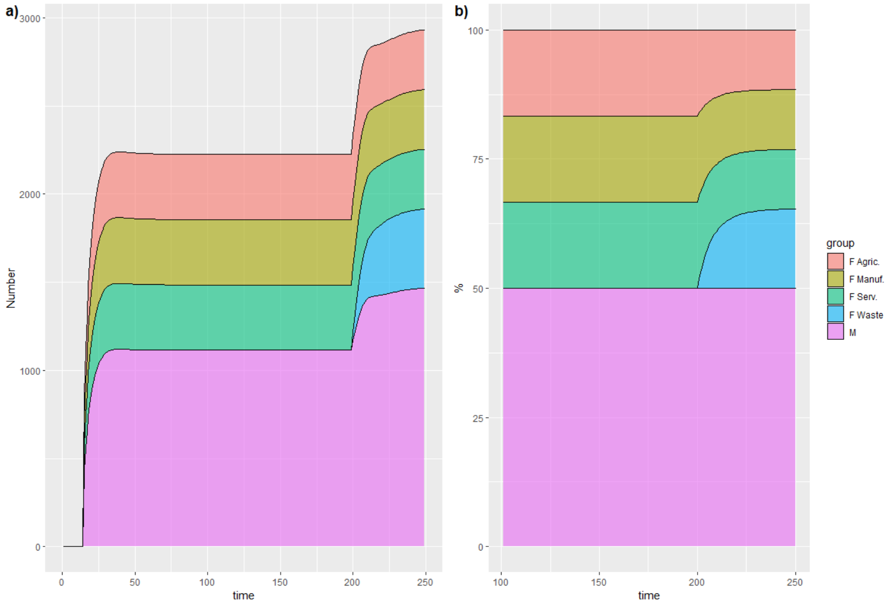
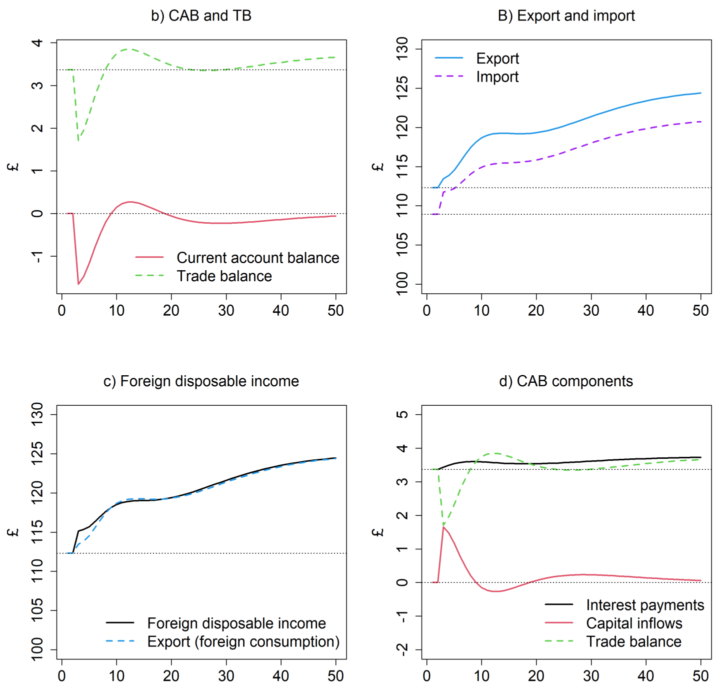


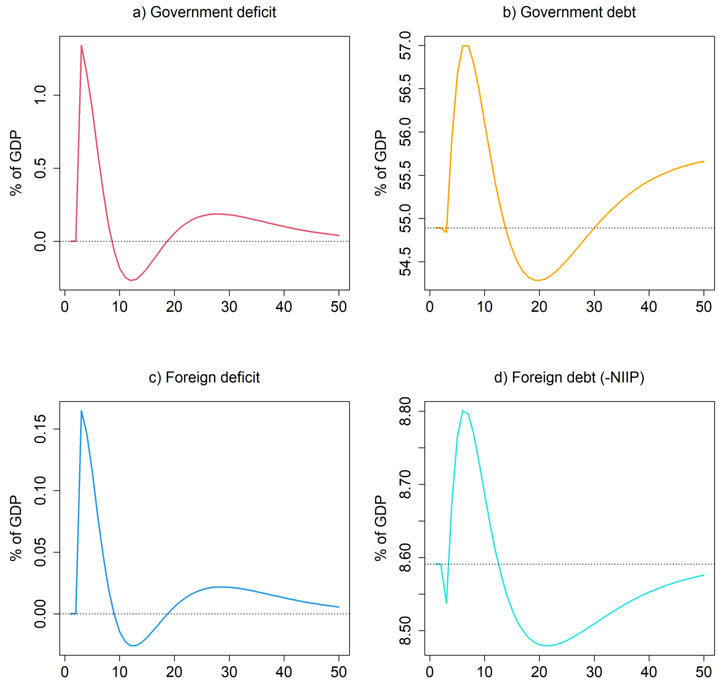
Figure 7: Current account balance and trade balance after CE



This model assumes that technical change (that is, the value of a'_{ij}) is set by the policy makers, while the average speed of convergence of technical coefficients to their target values is defined as a linear, positive function of government expenditures:

$$a_{ij} = a_{ij,-1} + \gamma_A \cdot (a'_{ij,-1} - a_{ij,-1}) \tag{69}$$

Figure 8: Internal and foreign debt after CE



$\forall\ i = 1,2,3,4$ and $j = 1,2,3,4$, where γ_A is the average speed of transition towards a (partial) CE production system, which is defined as:

$$\gamma_A = \gamma_A^0 + \Gamma_A^T \cdot \sigma \cdot gov_{-1} \tag{70}$$

where γ_A^0 is a positive scalar, whereas $\Gamma_A = \{\gamma_A^j\}$ is the vector that defines the industry-specific sensitivities (of the speeds of adjustment) to government final demands.[18]

Figure 4 shows that a CE innovation, triggered by a higher government spending, is associated with a change in relative prices. More precisely, the change in production techniques creates a brand-new market for "recycled waste", whose unit price tends to grow over time. By contrast, prices of other products and services decline. Unsurprisingly, the higher government spending and lower prices for consumer goods bring about an increase in real disposable income and consumption.

The higher production efficiency, due to the use of recycled waste as an intermediate good, reduces corporate demands for *traditional* inputs (manufacturing and agricultural products, plus services). However, CO_2 emissions increase in the short to medium run, because of the increase in total output (including recycled waste).[19] However, the use of more efficient techniques and the assumed lower energy intensity of waste recycling end up reducing emissions (compared with their baseline value) in the very long run, when the net product stabilises and total output even declines.

Turning to social variables, figure 5 shows that, other things being equal, the functional income distribution becomes more favorable to the workers. More precisely, there are two

[18] Notice that: $\sigma \cdot gov = \begin{pmatrix} \sigma_1 \\ \dots \\ \sigma_4 \end{pmatrix} \cdot gov = \begin{pmatrix} \sigma_1 \cdot gov \\ \dots \\ \sigma_4 \cdot gov \end{pmatrix}$.

[19] On the so-called *rebound effect*, see Zink and Geyer (2017)[9], and Bimpizas-Pinis et al. (2021).[1]

opposite effects. On the one hand, the higher stock of government debt is associated with an increase in the flow of interest payments to the rentiers, which affects the wage share to total income. On the other hand, the recycling industry is assumed to be more labour intensive than traditional industries. The second effect prevails here.[20] By contrast, gender equality is unchanged, although the absolute number of female workers increases (see also figure 6).[21] Once again, the effect is due to the higher labour intensity of the new recycling industry.

Notice that the behaviour of the foreign sector can influence the dynamics of the model as well. Figure 7 shows the evolution of selected variables following the CE innovation. As mentioned in section 2.6, real export dynamics is based on the assumption that the foreign agents have a target import (consumption) to wealth ratio. Besides, they hold all their savings in the form of home government bills. Home investors have more domestic options, but they cannot hold foreign assets. Because of that, the TB is always better than the CAB, as the latter includes the (negative) interest payments on home government bills held by the foreign sector. Once the CE innovation is introduced, import increases, as the fall in the demand for traditional inputs is dominated by recycling-driven economic growth in the short to medium run. The disposable income of foreign agents increases too, thus supporting home export. The home country runs a trade surplus in the long run, which eventually matches the higher (negative) interest payments, thus leaving the CAB unchanged.

Finally, focusing on public finances, figure 8 shows that the government deficit to GDP ratio increases in the short run, because of the higher government spending. However, the government sector balances its budget in the long run, thanks to the medium-run effect of economic growth. As a result, the government debt to GDP ratio tends to stabilize in the long run (and it even falls below its baseline value in the medium run). Similarly, the economy runs into a current account deficit in the short run (which is mostly the counterpart of the government deficit), but it tends to balance it in the long run, thus bringing its net international investment position back to the initial value.

5 Final remarks

Simplified though it is, the model presented above provides an intuitive and sound basis for developing more sophisticated IO-SFC dynamic models. A variety of sectors, industries, products and financial assets, as well as ecosystem-related variables, can be easily factored in. Unlike standard SFC models, the proposed model allows dealing with cross-industry interdependencies. Unlike traditional IO models, it allows endogenizing technical innovations, by linking the changes in technical coefficients with other variables – such as policy decisions, the evolution of demand conditions, portfolio decisions, and the change in the ecosystem. As a result, a variety of feedback effects can be explicitly modeled. The simple exercise proposed here confirms that the transition towards a CE system cannot rely on higher production efficiency only, due to rebound effects. Its impact on social variables is also ambiguous, as it depends on several factors (such as foreign trade and financial flows), some of which are not under the direct control of the policy makers in a market economy.

[20] Labour intensities are uniform across traditional industries.
[21] Gender shares are uniform across all industries.

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A Additional tables

Table 5: Identification of parameters and initial values for variables

Symbol	Definition	Baseline	CE Scenario
gov_0	Autonomous government spending	180.000	180.000
g_g	Growth rate of government spending	0.000	0.000
α_1	Propensity to consume out of wages	0.700	0.700
α_2	Propensity to consume out of profits	0.700	0.700
α_3	Propensity to consume out of wealth stock	0.400	0.400
α_4	Propensity to export out of foreign income	0.700	0.700
α_5	Propensity to export out of foreign wealth	0.400	0.400
θ	Average tax rate on income	0.200	0.200
r_m	Interest rate on deposits	0.020	0.020
r_l	Interest rate on loans	0.040	0.040
r_b	Interest rate on bills	0.040	0.040
λ_0	Fixed proportion of government bills to total wealth	0.100	0.100
λ_1	Sensitivity of portfolio choices to interest rate on deposits	0.000	0.000
λ_2	Sensitivity of portfolio choices to interest rate on bills	0.000	0.000
λ_3	Sensitivity of portfolio choices to transactions demand for money	0.000	0.000
λ_c	Cash to consumption ratio	0.100	0.100
ρ_1	Percentage of female workers in manufacturing industry	0.500	0.500
ρ_2	Percentage of female workers in agriculture	0.500	0.500
ρ_3	Percentage of female workers in services	0.500	0.500
ρ_4	Percentage of female workers in waste recycling industry	0.500	0.500
pr_1	Labour productivity in manufacturing industry	0.800	0.800
pr_2	Labour productivity in agriculture	0.800	0.800
pr_3	Labour productivity in services industry	0.800	0.800
pr_3	Labour productivity in waste recycling industry	0.200	0.200
μ_1	Mark-up in manufacturing industry	0.667	0.667
μ_2	Mark up in agriculture	0.667	0.667
μ_3	Mark up in services	0.667	0.667
μ_4	Costing margin in waste recycling industry	0.667	0.667
w	Wage rate	0.200	0.200
a_{11}	Manufacturing inputs in manufacturing industry	0.150	0.100
a_{12}	Agricultural inputs in manufacturing industry	0.150	0.100
a_{13}	Services inputs in manufacturing industry	0.150	0.100
a_{14}	Recycling inputs in manufacturing industry	0.000	0.100
a_{21}	Manufacturing inputs in agriculture	0.150	0.100
a_{22}	Agricultural inputs in agriculture	0.150	0.100
a_{23}	Services inputs in agriculture	0.150	0.100
a_{24}	Recycling inputs in agriculture	0.000	0.100
a_{31}	Manufacturing inputs in services industry	0.150	0.100
a_{32}	Agricultural inputs in services industry	0.150	0.100
a_{33}	Services inputs in services industry	0.150	0.100
a_{34}	Recycling inputs in services industry	0.000	0.100
a_{41}	Manufacturing inputs in waste recycling industry	0.000	0.100
a_{42}	Agricultural inputs in waste recycling industry	0.000	0.100
a_{43}	Services inputs in waste recycling industry	0.000	0.100
a_{44}	Recycling inputs in waste recycling industry	0.000	0.000
σ_1	Share of manufacturing in government consumption	0.333	0.333
σ_2	Share of agricultural products in government consumption	0.333	0.333
σ_3	Share of services in government consumption	0.333	0.333
β_1	Share of manufacturing in household consumption	0.333	0.333
β_2	Share of agricultural products in household consumption	0.333	0.333

β_3	Share of services in household consumption	0.333	0.333
η_1	Share of manufacturing in export	0.333	0.333
η_2	Share of agricultural products in export	0.333	0.333
η_3	Share of services in export	0.333	0.333
ι_1	Share of manufacturing in investment	0.333	0.333
ι_2	Share of agricultural products in investment	0.333	0.333
ι_3	Share of services in investment	0.333	0.333
ε_1	Energy intensity in domestic manufacturing industry	0.700	0.700
ε_2	Energy intensity in domestic agriculture	0.700	0.700
ε_3	Energy intensity in domestic services	0.700	0.700
ε_4	Energy intensity in waste recycling	0.600	0.600
ε_{1fo}	Energy intensity in foreign manufacturing industry	0.700	0.700
ε_{2fo}	Energy intensity in foregin agriculture	0.700	0.700
ε_{3fo}	Energy intensity in foreing services	0.700	0.700
β_e	CO_2 intensity of energy	0.070	0.070
ϕ_{11}	CO_2 transfer coefficient	0.982	0.982
ϕ_{12}	CO_2 transfer coefficient	0.018	0.018
ϕ_{21}	CO_2 transfer coefficient	0.008	0.008
ϕ_{22}	CO_2 transfer coefficient	0.991	0.991
ϕ_{23}	CO_2 transfer coefficient	0.0005	0.0005
ϕ_{32}	CO_2 transfer coefficient	0.0001	0.0001
ϕ_{33}	CO_2 transfer coefficient	0.999	0.999
ζ_1	Waste coefficient in domestic manufacturing industry	0.130	0.130
ζ_2	Waste coefficient in domestic agriculture	0.130	0.130
ζ_3	Waste coefficient in domestic services	0.130	0.130
ζ_{1fo}	Waste coefficient in foreign manufacturing industry	0.130	0.130
ζ_{2fo}	Waste coefficient in foreign agriculture	0.130	0.130
ζ_{3fo}	Waste coefficient in foreign services	0.130	0.130
δ	Depreciation of fixed capital	0.050	0.050
κ_1	Target fixed capital to manufacturing output ratio	0.070	0.070
κ_2	Target fixed capital to agricultural output ratio	0.070	0.070
κ_3	Target fixed capital to services output ratio	0.070	0.070
κ_4	Target fixed capital to recycling output ratio	0.070	0.070
γ	Speed of adjustment of current capital to target level	0.150	0.150
γ_{p1}	Stickiness of manufacturing products prices	0.500	0.500
γ_{p2}	Stickiness of agricultural products prices	0.500	0.500
γ_{p3}	Stickiness of services prices	0.500	0.500
γ_{p4}	Stickiness of recycled waste prices	0.500	0.500
γ_A^0	Autonomous speed of adjustment to new technical coefficients	0.000	0.000
γ_A^1	Government spending-sensitivity of speed of adjustment to new technical coefficients for manufacturing	0.0005	0.0005
γ_A^2	Government spending-sensitivity of speed of adjustment to new technical coefficients for agriculture	0.0005	0.0005
γ_A^3	Government spending-sensitivity of speed of adjustment to new technical coefficients for services	0.0005	0.0005
γ_A^4	Government spending-sensitivity of speed of adjustment to new technical coefficients for recycling	0.0005	0.0005
γ_μ	Speed of adjustment of recycling industry mark-up to average mark-up of other industries of the economy	0.200	0.2000

For additional information, visit:

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