Stock-flow consistent modelling and ecological macroeconomics

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Over the last years, stock-flow consistent (SFC) modelling has become a very popular approach in heterodox macro modelling (Caverzasi and Godin, 2015; Nikiforos and Zezza, 2017).

The SFC approach has proved successful in formulating the complex interactions between the financial and the real spheres of the economy.

This approach has its origins to the work of the Yale group of James Tobin and the Cambridge Economic Policy Group of Wynne Godley that used SFC structures to analyse the US and the UK economy in the 1970s and the 1980s.
There is currently a lot of research on theoretical SFC modelling. This is partly explained by the fact that SFC models are characterised by a high flexibility that allows them to be deployed for the analysis of a wide range of topics.

There is also research on empirical SFC modelling. However, the empirical SFC literature is much less developed than the theoretical one.

Recently, SFC models have been used for the analysis of ecological macroeconomic issues.

SFC models are currently viewed as alternative models to the DSGE models (especially when they are combined with agent-based structures).
The aims of this lecture are:

1. To provide an introduction to the features and the methodology of SFC models. Particular emphasis will be placed on the steps that need to be followed in practice in order to construct and simulate SFC models.

2. To present how ecological aspects can be incorporated into SFC models.
Outline

1. Features of SFC models
2. Steps in developing an SFC model
3. Steps in simulating an SFC model
4. Incorporating ecological aspects into SFC models
5. The DEFINE model
6. Conclusion
Outline

1. Features of SFC models
2. Steps in developing an SFC model
3. Steps in simulating an SFC model
4. Incorporating ecological aspects into SFC models
5. The DEFINE model
6. Conclusion
(1) There are no black holes

‘Everything comes from somewhere and goes somewhere’. This is ensured by using two matrices: (i) the balance sheet matrix and (ii) the transactions flow matrix.

(2) The financial and the real spheres are integrated

Following the post-Keynesian tradition on the non-neutrality of money and finance, the SFC models explicitly formulate the various links between financial and real variables.

(3) Behavioural equations are based on post-Keynesian assumptions

The behavioural equations (like consumption and investment function) are constructed following post-Keynesian theories.
(1) There are no black holes

Balance sheet matrix

<table>
<thead>
<tr>
<th></th>
<th>Households</th>
<th>Firms</th>
<th>Commercial banks</th>
<th>Central bank</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposits</td>
<td>+D</td>
<td></td>
<td>-D</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Loans</td>
<td></td>
<td>-L</td>
<td>+L</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Equities</td>
<td>+p_e e</td>
<td>-p_e e</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Capital</td>
<td>+K</td>
<td></td>
<td></td>
<td></td>
<td>+K</td>
</tr>
<tr>
<td>High-powered money</td>
<td></td>
<td></td>
<td>+HPM</td>
<td>-HPM</td>
<td>0</td>
</tr>
<tr>
<td>Advances</td>
<td></td>
<td>-A</td>
<td>+A</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Total (net worth)</td>
<td>+V_H</td>
<td>+V_F</td>
<td>0</td>
<td>+V_Cb</td>
<td>+K</td>
</tr>
</tbody>
</table>
(1) There are no black holes

Transactions flow matrix

<table>
<thead>
<tr>
<th></th>
<th>Households</th>
<th>Firms</th>
<th>Commercial banks</th>
<th>Central bank</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Current</td>
<td>Capital</td>
<td>Current</td>
<td>Capital</td>
</tr>
<tr>
<td><strong>Consumption</strong></td>
<td>-C</td>
<td>+C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Investment</strong></td>
<td></td>
<td>+I</td>
<td>-I</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Wages</strong></td>
<td>+W</td>
<td>-W</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Firms' profits</strong></td>
<td>+DP</td>
<td>-TP</td>
<td>+RP</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Banks' profits</strong></td>
<td>+BP</td>
<td></td>
<td>-BP</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Central bank's profits</strong></td>
<td></td>
<td></td>
<td></td>
<td>-CBP</td>
<td>+CBP</td>
</tr>
<tr>
<td><strong>Interest on deposits</strong></td>
<td>+int_D,1</td>
<td>-int_D,1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Interest on loans</strong></td>
<td>-int_L,1</td>
<td>+int_L,1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Interest on advances</strong></td>
<td>-int_A,1</td>
<td>+int_A,1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Change in deposits</strong></td>
<td>-ΔD</td>
<td></td>
<td></td>
<td>+ΔD</td>
<td></td>
</tr>
<tr>
<td><strong>Change in loans</strong></td>
<td></td>
<td>+ΔL</td>
<td>-ΔL</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Change in equities</strong></td>
<td>-p_eΔe</td>
<td>+p_eΔe</td>
<td></td>
<td>+ΔA</td>
<td>-ΔA</td>
</tr>
<tr>
<td><strong>Change in high-powered money</strong></td>
<td></td>
<td>-ΔHPM</td>
<td>+ΔHPM</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Change in advances</strong></td>
<td></td>
<td></td>
<td></td>
<td>+ΔA</td>
<td>-ΔA</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
(2) The financial and the real spheres are integrated

- The post-Keynesian SFC models integrate the real with the financial side of the economy.
- All SFC models have at least one financial asset/liability.
- Money is introduced both as a stock and as a flow variable.
- Two examples of the real sector-financial sector interlinkages:
  1. Financing of firms’ investment.
  2. Asset price effects on consumption and investment.
(2) The financial and the real spheres are integrated

- Firms take out loans to finance their investment.
- In most SFC models loans are provided upon demand. However, in some SFC models banks can also play a more active role via quantity and price credit rationing.
- Firms’ investment can also be funded via equities and bonds.
(2) The financial and the real spheres are integrated

- The **portfolio choice** (i.e. the allocation of wealth of households among financial assets) is determined by the (expected) relative rates of return and liquidity preference.

- The portfolio choice can affect the **price of financial assets** (e.g. government bonds or equities) having feedback effects on consumption (since wealth is incorporated in the consumption function) and investment (if, for example, Tobin’s q is included in the investment function).
(3) Behavioural equations are based on post-Keynesian assumptions

- Labour and product markets do not clear through changes in wages and prices (as in neoclassical models). On the contrary, they clear via the **adjustment of supply to demand**.

- The **pricing mechanism** only plays a clearing role in the **financial markets**.

- Although the post-Keynesian SFC models are primarily demand-led, it is possibly to introduce **supply-side** effects (e.g. by including a Phillips curve).
(3) Behavioural equations are based on post-Keynesian assumptions

- The decisions of households are formulated using Davidson’s two-step decision process: The 1st step refers to the decision about the proportion of income that will be saved. The 2nd step refers to the way that savings will be allocated between the various assets (portfolio choice).

- In many behavioural equations economic agents have stock-flow targets (e.g. wealth-to-income ratios, debt-to-income ratios, inventories-to-sales ratios) and react to disequilibria in order to achieve these targets.

- Behaviour can be different between classes.

- There is no intertemporal utility maximisation.
## Key differences between SFC and DSGE models

<table>
<thead>
<tr>
<th>DSGE models</th>
<th>Post-Keynesian SFC models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply-determined output</td>
<td>Demand-determined output (with supply-side constraints)</td>
</tr>
<tr>
<td>Banks are financial intermediaries</td>
<td>Money is endogenous</td>
</tr>
<tr>
<td>Utility and profit maximisation</td>
<td>Fundamental uncertainty/bounded rationality</td>
</tr>
<tr>
<td>Income distribution does not typically matter</td>
<td>Income distribution affects economic activity</td>
</tr>
</tbody>
</table>
Outline

1. Features of SFC models
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Steps in developing an SFC model

- **Step 1**: Construct the balance sheet matrix.
- **Step 2**: Construct the transactions flow matrix.
- **Step 3**: Write down the identities from the transactions flow matrix. Use the columns (which reflect the budget constraints) and the rows with more than two entries. Identify the buffer variables in the identities.
- **Step 4**: Identify the variables that need to be determined based on behavioural equations. Select your behavioural equations.
- **Step 5**: Put together the identities and the behavioural equations.
Suppose that we have an economy with the following features:

- There are four sectors: firms, households, banks and a central bank.
- **Firms** make investment by using retained profits, loans and equity. A part of firms’ profits is distributed to households.
- **Households** accumulate savings in the form of deposits and equity.
- **Banks** provide firm loans by creating deposits. Banks’ profits are distributed to households.
- **Central bank** holds advances on the asset side of its balance sheet and high-powered money on the liability side.

This is a model with both private bank money and central bank money.
**Step 1: Construct the balance sheet matrix.**

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<td></td>
<td>-D</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Loans</td>
<td></td>
<td>-L</td>
<td>+L</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Equities</td>
<td>+p_e</td>
<td>-p_e</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Capital</td>
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<tr>
<td>Total (net worth)</td>
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<td></td>
<td>0</td>
</tr>
<tr>
<td>Equities</td>
<td>+p_e</td>
<td>-p_e</td>
<td></td>
<td></td>
<td>0</td>
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<td>0</td>
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<td>+K</td>
</tr>
</tbody>
</table>

**Question:** How would you modify this balance sheet matrix in order to analyse (1) income distribution, (2) the housing market and (3) shadow banking?
• **Income distribution:** Zezza (2008), van Treeck (2009), Dafermos and Papatheodorou (2015), Kapeller et al. (2017)

• **Housing market:** Zezza (2008), Nikolaidi (2015), Ryoo (2016)

• **Shadow banking:** Eatwell et al. (2008), Lavoie (2014), Nikolaidi (2015), Botta et al. (2018, 2019)
### Step 2: Construct the transactions flow matrix.

<table>
<thead>
<tr>
<th></th>
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<th>Firms</th>
<th>Commercial banks</th>
<th>Central bank</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Consumption</strong></td>
<td>(-C)</td>
<td>+C</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td><strong>Investment</strong></td>
<td>(+I)</td>
<td>-I</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td><strong>Wages</strong></td>
<td>(+W)</td>
<td>-W</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td><strong>Firms' profits</strong></td>
<td>(+DP)</td>
<td>-TP</td>
<td>+RP</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td><strong>Banks' profits</strong></td>
<td>(+BP)</td>
<td>-BP</td>
<td></td>
<td>-CBP</td>
<td>0</td>
</tr>
<tr>
<td><strong>Central bank's profits</strong></td>
<td>+int(<em>1)D(</em>-1)</td>
<td>-int(<em>1)D(</em>-1)</td>
<td>+int(<em>1)L(</em>-1)</td>
<td>-int(<em>1)A(</em>-1) +int(<em>1)A(</em>-1)</td>
<td>0</td>
</tr>
<tr>
<td><strong>Interest on deposits</strong></td>
<td>int(<em>1)D(</em>-1)</td>
<td>-int(<em>1)D(</em>-1)</td>
<td>+int(<em>1)L(</em>-1)</td>
<td>-int(<em>1)A(</em>-1) +int(<em>1)A(</em>-1)</td>
<td>0</td>
</tr>
<tr>
<td><strong>Interest on loans</strong></td>
<td>-int(<em>1)L(</em>-1)</td>
<td>+int(<em>1)L(</em>-1)</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td><strong>Interest on advances</strong></td>
<td>-int(<em>1)A(</em>-1)</td>
<td>+int(<em>1)A(</em>-1)</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td><strong>Change in deposits</strong></td>
<td>(-\Delta D)</td>
<td></td>
<td>+\Delta D</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td><strong>Change in loans</strong></td>
<td></td>
<td>(+\Delta L)</td>
<td>(-\Delta L)</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td><strong>Change in equities</strong></td>
<td>-(p_a\Delta e)</td>
<td>(+p_a\Delta e)</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td><strong>Change in high-powered money</strong></td>
<td></td>
<td></td>
<td>-(\Delta HPM)</td>
<td>(+\Delta HPM)</td>
<td>0</td>
</tr>
<tr>
<td><strong>Change in advances</strong></td>
<td></td>
<td>(+\Delta A)</td>
<td>(-\Delta A)</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Step 3: Write down the identities from the transactions flow matrix. Use the columns (which reflect the budget constraints) and the rows with more than two entries. Identify the buffer variables in the identities.

\[
\Delta D = Y_D - C - p_e \Delta e \\
TP = Y - W - \text{int}_L L_{-1} \\
\Delta L = I - \text{RP} - p_e \Delta e \\
BP = \text{int}_L L_{-1} - \text{int}_D D_{-1} - \text{int}_A A_{-1} \\
\Delta A = \Delta \text{HPM} + \Delta L - \Delta D \\
\text{CBP} = \text{int}_A A_{-1} \\
\Delta A = \Delta \text{HPM} + \text{CBP} \\
DP = TP - \text{RP}
\]
**Step 4:** Identify the variables that need to be determined based on behavioural equations. Select your behavioural equations.

- Wage income of households: $W$
- Disposable income of households: $Y_D$
- Consumption expenditures: $C$
- Wealth (identity): $V_H$
- Deposits (identity): $D$
- Income: $Y$
- Total profits of firms (identity): $TP$
- Retained profits: $RP$
- Distributed profits (identity): $DP$
- Investment: $I$
- Capital stock: $K$
- Loans (identity): $L$
- Number of equities: $e$
- Price of equities: $p_e$
- Profits of banks (identity): $BP$
- High-powered money: $HPM$
- Advances (identity): $A$
- Profits of central bank (identity): $CBP$
- Wage income of households: \( W = s_W Y \)
- Consumption expenditures: \( C = c_1 Y_{D-1} + c_2 V_{H-1} \)
- Retained profits: \( RP = s_F TP_{-1} \)
- Investment: \( I = g_K K_{-1} \)
- Capital stock: \( K = K_{-1} + I \)
- Value of equity held by households:
  \[
  E = (\lambda_0 + \lambda_1 r_{e-1} + \lambda_2 int_D + \lambda_3 (Y_{D-1}/V_{H-1}))V_{H-1}
  \]
- Number of equities: \( e = e_{-1} + \frac{xI_{-1}}{p_e} \)
- Price of equities: \( p_e = \frac{E}{e} \)
- High-powered money: \( HPM = hD \)
Step 5: Put together the identities and the behavioural equations. **Households**

- Wage income of households: \( W = s W Y \)
- Disposable income of households:
  \( Y_D = W + DP + BP + \text{int}_D D_{-1} \)
- Consumption expenditures:
  \( C = c_1 Y_{D-1} + c_2 V_{H-1} \)
- Wealth (identity):
  \( V_H = D + p_e e \)
- Value of equity held by households:
  \( E = (\lambda_0 + \lambda_1 r_{e-1} + \lambda_2 \text{int}_D + \lambda_3 (Y_{D-1}/V_{H-1})) V_{H-1} \)
- Deposits (identity):
  \( D = D_{-1} + Y_D - C - p_e \Delta e \)
Firms

- Income: \( Y = C + I \)
- Total profits of firms (identity): \( TP = Y - W - \text{int}_L L_{-1} \)
- Retained profits: \( RP = s_F TP_{-1} \)
- Distributed profits (identity): \( DP = TP - RP \)
- Investment: \( I = g_K K_{-1} \)
- Capital stock: \( K = K_{-1} + I \)
- Loans (identity): \( L = L_{-1} + I - RP - p_e \Delta e \)
- Number of equities: \( e = e_{-1} + \frac{xI_{-1}}{p_e} \)
- Price of equities: \( p_e = \frac{E}{e} \)
- Rate of return of firms: \( r_e = \frac{DP}{p_{e-1}e_{-1}} + \frac{\Delta p_e}{p_{e-1}} \)
Commercial banks

- Profits of banks (identity): $BP = \text{int}_L L_{-1} - \text{int}_D D_{-1} - \text{int}_A A_{-1}$
- High-powered money: $HPM = hD$
- Advances (identity): $A = HPM + L - D$

Central bank

- Profits of central bank (identity): $CBP = \text{int}_A A_{-1}$
- Advances (identity): $A_{red} = A_{-1} + \Delta HPM + CBP$
Useful tips - Consistency

- In order for your model to be consistent you need to ensure that:
  1. In the initial period all the stocks in the model satisfy the restrictions of the balance sheet matrix.
  2. The identities from the transactions flow matrix and balance sheet matrix are correctly written.
  3. The adding-up constraints are satisfied (if your model includes portfolio allocation).

- If the model is consistent, the redundant equation is satisfied.
Useful tips - Wealth and capital gains

- Deposits are determined by the following identity:
  \[ D = D_{-1} + Y_D - C - p_e \Delta e \] (1)

- Equation (1) can be rewritten as follows:
  \[ \Delta D + p_e \Delta e = Y_D - C \] (2)

- We know from the balance sheet matrix that the wealth of households is:
  \[ V_H = D + p_e e \] (3)

- Therefore, the change in the wealth of households is:
  \[ \Delta V_H = \Delta D + p_e \Delta e + e_{-1} \Delta p_e \] (4)

- By combining equations (2) and (4) we get:
  \[ V_H = V_{H-1} + Y_D - C + e_{-1} \Delta p_e \] (identity)
Useful tips - Equity market

Equations of the **portfolio choice**:

\[ E = (\lambda_{10} + \lambda_{11} r_e - 1 + \lambda_{12} r_b + \lambda_{13} \text{int}_D + \lambda_{14} (Y_{D-1}/V_{H-1}))V_{H-1} \]

\[ B = (\lambda_{20} + \lambda_{21} r_e - 1 + \lambda_{22} r_b + \lambda_{23} \text{int}_D + \lambda_{24} (Y_{D-1}/V_{H-1}))V_{H-1} \]

\[ D = (\lambda_{30} + \lambda_{31} r_e - 1 + \lambda_{32} r_b + \lambda_{33} \text{int}_D + \lambda_{34} (Y_{D-1}/V_{H-1}))V_{H-1} \]

where \( E \) is the value of equity, \( B \) are Treasury bills, \( D \) are deposits, \( V_H \) is wealth, \( Y_D \) is disposable income, \( r_e \) is the rate of return on equities, \( \text{int}_D \) is the interest rate on deposits and \( r_b \) is the interest on Treasury bills.
Useful tips - Equity market

- In the equity market we assume equilibrium:

\[ e = \frac{E}{p_e} \]

- By using the equation for the number of equities in the previous equation we get:

\[ e_{-1} + \frac{xI_{-1}}{p_e} = \frac{E}{p_e} \]

- By rearranging we have the following equation for the price of equities:

\[ p_e = \frac{E - xI_{-1}}{e_{-1}} \]
Useful tips - Steady state of the model

At the steady state all flow-stock, stock-flow, flow-flow and stock-stock ratios (e.g. $Y/K$, $L/K$, $M/Y$) are constant. For example:

$$\Delta \left( \frac{Y}{K} \right) = \frac{Y}{K} - \frac{Y_{-1}}{K_{-1}} = \frac{Y}{K} - \frac{Y_{-1}(1+g_K)}{K} = \frac{\Delta Y - g_K Y_{-1}}{K} = \frac{\Delta Y}{K} - \frac{Y}{(1+g_K)}$$

Since $Y/K$ should be constant at the steady state, we need $\Delta \left( \frac{Y}{K} \right) = 0$. 
## Outline

1. Features of SFC models
2. Steps in developing an SFC model
3. Steps in simulating an SFC model
4. Incorporating ecological aspects into SFC models
5. The DEFINE model
6. Conclusion
- SFC models can be simulated using various software programmes (e.g. EViews, R, Excel or MATLAB).
- SFC models can be either discrete-time or continuous-time models.
- When SFC models are small we can solve them analytically (e.g. by finding the steady-states and conducting stability analysis).
- When SFC models are large in most cases we use numerical simulations.
Steps in simulating an SFC model

- **Step 1**: Identify the endogenous variables of the model (as well as some auxiliary variables).

- **Step 2**: Identify the baseline scenario and select the parameter values (see the table below).

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A)</td>
<td>Econometrically estimated parameters</td>
</tr>
<tr>
<td>(B)</td>
<td>Directly calibrated parameters</td>
</tr>
<tr>
<td>(Bi)</td>
<td>Based on data</td>
</tr>
<tr>
<td>(Bii)</td>
<td>Based on previous studies</td>
</tr>
<tr>
<td>(Biii)</td>
<td>Selected from a reasonable range of values</td>
</tr>
<tr>
<td>(C)</td>
<td>Indirectly calibrated parameters</td>
</tr>
<tr>
<td>(Ci)</td>
<td>Calibrated such that the model matches the data</td>
</tr>
<tr>
<td>(Cii)</td>
<td>Calibrated such that the model generates the baseline scenario</td>
</tr>
</tbody>
</table>
Steps in simulating an SFC model

- **Step 3**: Select the initial values using the data for your economy or the equations of the model.
- **Step 4**: Write down the equations and run the model.
- **Step 5**: Report your results by using tables and graphs.
- **Step 6**: Validate the model by using your baseline scenario. Validation can be conducted, for example, by estimating the volatility, the auto-correlation and the cross-correlation for some key variables.
- **Step 7**: Re-run the simulations by changing key parameters (sensitivity analysis).
- **Step 8**: Re-run the simulations by changing parameters that correspond to policies/institutional structures.
Outline

1. Features of SFC models
2. Steps in developing an SFC model
3. Steps in simulating an SFC model
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6. Conclusion
• Traditional SFC models are not in line with ecological macroeconomics.

• They ignore the fact that production and consumption are not possible without using energy and matter.

• They do not take into account that economic activity creates various types of waste that can destabilise the ecosystem.

• They also neglect other types of environmental problems, like the loss of biodiversity, water scarcity and deforestation.
There are two ways/steps to incorporate ecological aspects in SFC models:

1. To make a distinction between ‘green’ and ‘conventional’ investment, products and financial instruments (e.g. loans, bonds).

2. To incorporate physical stocks and flows (energy, matter, waste etc.) and their interactions with the economy.
(1) Introducing green activities

How can green activities be included in an SFC model?

- **Way 1:** By assuming that the firm sector can produce both green and conventional goods and can issue green financial instruments and take out green loans.

- **Way 2:** By decomposing the firm sector, making a distinction between green and conventional firms.
(1) Introducing green activities

### Balance sheet matrix

<table>
<thead>
<tr>
<th></th>
<th>Households</th>
<th>Firms</th>
<th>Commercial banks</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposits</td>
<td>+D</td>
<td></td>
<td>-D</td>
<td>0</td>
</tr>
<tr>
<td>Green loans</td>
<td></td>
<td>-L_G</td>
<td>+L_G</td>
<td>0</td>
</tr>
<tr>
<td>Conventional loans</td>
<td></td>
<td>-L_C</td>
<td>+L_C</td>
<td>0</td>
</tr>
<tr>
<td>Green capital</td>
<td></td>
<td>+K_G</td>
<td></td>
<td>+K_G</td>
</tr>
<tr>
<td>Conventional capital</td>
<td></td>
<td>+K_C</td>
<td></td>
<td>+K_C</td>
</tr>
<tr>
<td>Total (net worth)</td>
<td>+D</td>
<td>+V_F</td>
<td>0</td>
<td>+K</td>
</tr>
</tbody>
</table>
(1) Introducing green activities

### Transactions flow matrix

<table>
<thead>
<tr>
<th></th>
<th>Households</th>
<th>Firms</th>
<th>Commercial banks</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current</td>
<td>Capital</td>
<td>Current</td>
<td>Capital</td>
</tr>
<tr>
<td>Consumption</td>
<td>-C</td>
<td>+C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green investment</td>
<td></td>
<td>+I_G</td>
<td>-I_G</td>
<td></td>
</tr>
<tr>
<td>Conventional investment</td>
<td></td>
<td>+I_C</td>
<td>-I_C</td>
<td></td>
</tr>
<tr>
<td>Wages</td>
<td>+W</td>
<td>-W</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Firms' profits</td>
<td>+DP</td>
<td>-TP</td>
<td>+RP</td>
<td></td>
</tr>
<tr>
<td>Banks' profits</td>
<td>+BP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interest on deposits</td>
<td>+int_D_{-1}</td>
<td>-BP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interest on green loans</td>
<td>-int_G_{-1}</td>
<td>+int_G_{-1}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interest on conventional loans</td>
<td>-int_C_{-1}</td>
<td>+int_C_{-1}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Change in deposits</td>
<td>-ΔD</td>
<td></td>
<td></td>
<td>+ΔD</td>
</tr>
<tr>
<td>Change in green loans</td>
<td></td>
<td>+ΔL_G</td>
<td>-ΔL_G</td>
<td></td>
</tr>
<tr>
<td>Change in conventional loans</td>
<td></td>
<td>+ΔL_C</td>
<td>-ΔL_C</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
(1) Introducing green activities

- Green investment can be modelled as a proportion ($\beta$) of total investment: $I_G = \beta I$
- $\beta$ can depend on a number of factors, like carbon prices, interest rates and regulation.
- **Credit conditions** for green and brown loans can be different.
- The accumulation of green capital compared to conventional capital can affect environmental variables, like carbon emissions.
(1) Introducing green activities

The introduction of green activities allows us to analyse scenarios like these ones:

- The **price of carbon** increases and, as a result, the cost for brown firms/brown activities goes up (Bovari et al., 2018; Monasterolo and Raberto, 2018; Dafermos and Nikolaidi, 2019a).

- Financial investors increase the share of **green stocks** in their portfolio (Campiglio et al., 2017).

- Banks increase **credit rationing** on brown loans (Dafermos and Nikolaidi, 2019b).
(2) Incorporating physical stocks and flows

- An integrated incorporation of environmental aspects into an SFC model requires the use of additional matrices, apart from the transactions and the balance sheet ones.
- The **physical flow matrix** captures the flows of energy and matter.
- The **physical stock-flow matrix** captures the interaction between physical stocks and flows.
- These matrices draw on the work of Georgescu-Roegen (1971) and rely on the laws of thermodynamics.
(2) Incorporating physical stocks and flows

Material flows

**Inputs**
- Oxygen ($O_2$)
- Extracted Matter ($M$)
- Carbon mass of non-renewable energy ($CEN$)

**Socio-economic system**
- Matter necessary for production ($MY$)
- Production process
- Demolished/discarded SES ($DEM$)
- Socio-economic stock ($SES$)
- Recycled socio-economic stock ($REC$)

**Outputs**
- Industrial CO$_2$ emissions ($EMIS_{IN}$)
- Waste management
- Waste ($W$)
(2) Incorporating physical stocks and flows

**Physical flow matrix**

<table>
<thead>
<tr>
<th></th>
<th>Material balance</th>
<th>Energy balance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inputs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extracted matter</td>
<td>+M</td>
<td></td>
</tr>
<tr>
<td>Renewable energy</td>
<td></td>
<td>+ER</td>
</tr>
<tr>
<td>Non-renewable energy</td>
<td>+CEN</td>
<td>+EN</td>
</tr>
<tr>
<td>Oxygen used for fossil fuel combustion</td>
<td>+O2</td>
<td></td>
</tr>
<tr>
<td><strong>Outputs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Industrial CO(_2) emissions</td>
<td>-EMIS(_{IN})</td>
<td></td>
</tr>
<tr>
<td>Waste</td>
<td>-W</td>
<td>-ED</td>
</tr>
<tr>
<td>Dissipated energy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Change in socio-economic stock</td>
<td>-(\Delta SES)</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

- Material balance: \(M+CEN+O2=EMIS\(_{IN}\)+W+\Delta SES\)
- Energy balance: \(ER+EN=ED\)
(2) Incorporating physical stocks and flows

<table>
<thead>
<tr>
<th>Physical stock-flow matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material reserves</strong></td>
</tr>
<tr>
<td>Opening stock</td>
</tr>
<tr>
<td>Additions to stock</td>
</tr>
<tr>
<td>Resources converted into reserves</td>
</tr>
<tr>
<td>CO₂ emissions</td>
</tr>
<tr>
<td>Production of material goods</td>
</tr>
<tr>
<td>Non-recycled hazardous waste</td>
</tr>
<tr>
<td>Reductions of stock</td>
</tr>
<tr>
<td>Extraction/use of matter or energy</td>
</tr>
<tr>
<td>Net transfer of CO₂ to oceans/biosphere</td>
</tr>
<tr>
<td>Demolished/disposed socio-economic stock</td>
</tr>
<tr>
<td>Closing stock</td>
</tr>
</tbody>
</table>

- Material reserves: REVₘ₋₁ + CONₘ-M = REVₘ
- Non-renewable energy reserves: REVₑ₋₁ + CONₑ-EN = REVₑ
- Atmospheric CO₂ concentration:
  EMIS + φ₁₁CO₂₄₆₋₁ + φ₂₁CO₂₄₆₋₁ = CO₂₄₆
- Socio-economic stock: SES₋₁ + MY-DEM = SES
- Hazardous waste: HWS₋₁ + hazW = HWS
(2) Incorporating physical stocks and flows

Economic growth \rightarrow \text{Use of non-renewable energy} \rightarrow \text{Carbon emissions} \rightarrow \text{Carbon concentration}
(2) Incorporating physical stocks and flows

The carbon cycle

- Atmosphere
  - Upper ocean/biosphere
    - Lower ocean
2) Incorporating physical stocks and flows

- Industrial CO$_2$ emissions (EMIS$_{IN}$) are generated when the non-renewable energy resources (EN) are used to produce energy: $\text{EMIS}_{IN} = \omega \text{EN}$
- The stock of carbon that remains in the atmosphere depends on the carbon cycle:

\[
\text{CO}_2 \text{ concentration in the atmosphere: } \text{CO}_2_{AT} = \text{EMIS} + \phi_{11} \text{CO}_2_{AT-1} + \phi_{21} \text{CO}_2_{UP-1}
\]

\[
\text{CO}_2 \text{ concentration in the upper ocean/biosphere: } \text{CO}_2_{UP} = \phi_{12} \text{CO}_2_{AT-1} + \phi_{22} \text{CO}_2_{UP-1} + \phi_{32} \text{CO}_2_{LO-1}
\]

\[
\text{CO}_2 \text{ concentration in the lower ocean: } \text{CO}_2_{LO} = \phi_{23} \text{CO}_2_{UP-1} + \phi_{33} \text{CO}_2_{LO-1}
\]
(2) Incorporating physical stocks and flows

- Economic growth
- Use of non-renewable energy
- Carbon emissions
- Radiative forcing
- Carbon concentration
(2) Incorporating physical stocks and flows

The atmospheric CO$_2$ concentration affects radiative forcing (F), which is the difference between the sunlight absorbed by the Earth and the energy radiated back to the space:

$$F = F_{2\times CO_2} \log_2 \frac{CO_2_{AT}}{CO_2_{AT-PRE}} + F_{EX}$$

$F_{2\times CO_2}$: Increase in radiative forcing (since the pre-industrial period) due to doubling of CO$_2$ concentration from pre-industrial levels (W/m$^2$)

$CO_2_{AT-PRE}$: Pre-industrial atmospheric CO$_2$ concentration

$F_{EX}$: Radiative forcing, over pre-industrial levels, due to non-CO$_2$ greenhouse gases (W/m$^2$)
(2) Incorporating physical stocks and flows

- Economic growth
- Use of non-renewable energy
- Carbon emissions
- Atmospheric temperature
- Radiative forcing
- Carbon concentration
(2) Incorporating physical stocks and flows

Radiative forcing affects **atmospheric temperature** \( (T_{AT}) \):

\[
T_{AT} = T_{AT-1} + t_1 \left[ F - \frac{F_{CO_2}}{S} T_{AT-1} - t_2 (T_{AT-1} - T_{LO-1}) \right]
\]

*\( S \): Equilibrium climate sensitivity, i.e. increase in equilibrium temperature due to doubling of \( \text{CO}_2 \) concentration from pre-industrial levels (\(^\circ\text{C}\))

*\( T_{LO} \): Lower ocean temperature over pre-industrial levels (\(^\circ\text{C}\))
(2) Incorporating physical stocks and flows

**Question for discussion:** What are the feedback effects of climate change on economic activity? Think about both demand-side and supply-side effects.
## (2) Incorporating physical stocks and flows

### Feedback effects of climate change on the economy

<table>
<thead>
<tr>
<th>Type of shock</th>
<th>From gradual global warming</th>
<th>From extreme weather events</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Demand</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Investment</td>
<td>Uncertainty about future demand and climate risks</td>
<td>Uncertainty about climate risks</td>
</tr>
<tr>
<td><strong>Consumption</strong></td>
<td>Changes in consumption patterns, e.g. more savings for hard times</td>
<td>Increased risk of flooding to residential property</td>
</tr>
<tr>
<td><strong>Trade</strong></td>
<td>Changes in trade patterns due to changes in transport systems and economic activity</td>
<td>Disruption to import/export flows due to extreme weather events</td>
</tr>
<tr>
<td><strong>Supply</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Labour supply</td>
<td>Loss of hours worked due to extreme heat. Labour supply shock from migration</td>
<td>Loss of hours worked due to natural disasters, or mortality in an extreme case. Labour supply shock from migration</td>
</tr>
<tr>
<td><strong>Energy, food and other inputs</strong></td>
<td>Decrease in agricultural productivity</td>
<td>Food and other input shortages</td>
</tr>
<tr>
<td>Capital stock</td>
<td>Diversion of resources from productive investment to adaptation capital</td>
<td>Damage due to extreme weather</td>
</tr>
<tr>
<td>Technology</td>
<td>Diversion of resources from innovation to adaptation capital</td>
<td>Diversion of resources from innovation to reconstruction and replacement</td>
</tr>
</tbody>
</table>

Source: NGFS (2019)
(2) Incorporating physical stocks and flows

- The feedback effects of the environment on the economy can be incorporated through **damage functions**.
- In **mainstream environmental models** the damages are confined to the supply side and tend to be optimistic.
- In **SFC models** damages refer both to the demand and the supply side and tend to be more pessimistic.
- The incorporation of damages remains a very challenging task and we are still far from formulating them properly.
Mainstream vs ecol. macro SFC models

Key differences between IAMs/CGE and ecol. macro SFC models

<table>
<thead>
<tr>
<th>IAMs/CGE models</th>
<th>SFC ecological macro models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply-determined output</td>
<td>Demand-determined output (with supply-side constraints)</td>
</tr>
<tr>
<td>Banks are financial intermediaries</td>
<td>Money is endogenous</td>
</tr>
<tr>
<td>Utility and profit maximisation</td>
<td>Fundamental uncertainty/bounded rationality</td>
</tr>
<tr>
<td>Income distribution does not typically matter</td>
<td>Income distribution affects economic activity</td>
</tr>
<tr>
<td>Mitigation represents only a cost</td>
<td>Mitigation is both a cost and a source of income</td>
</tr>
<tr>
<td>Environmental problems as externalities</td>
<td>Systems approach to the environmental issues</td>
</tr>
</tbody>
</table>
Outline

1. Features of SFC models
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The **DEFINE** (Dynamic Ecosystem-FINance-Economy) model is an **SFC ecological macroeconomic model** that analyses the complex interactions between the macroeconomy, the financial system and the ecosystem (Dafermos, Nikolaidi and Galanis, 2017, 2018; Dafermos and Nikolaidi, 2019a, 2019b).

The model can be used for analysing the effects of a wide range of environmental policies.

For more information, see: [www.define-model.org](http://www.define-model.org)
The model consists of two big blocks and various sub-blocks.

**Ecosystem**
- Matter, waste and recycling
- Energy
- Emissions and climate change
- Ecological efficiency and technology

**Macroeconomy and financial system**
- Output determination
- Firms
- Households
- Banks
- Government sector
- Central banks
Calibration/estimation of the model:

- We use a mix of calibration and estimation techniques.
- We estimate some functions (such as investment and consumption) using panel data for the global economy.
- We calibrate some parameter values using data or other studies.
- We develop a baseline scenario and then conduct sensitivity and policy analysis.
Baseline scenario:

- Economic growth is, on average, slightly lower than 2.5% till 2050.
- Population becomes 9.77bn people in 2050.
- Very slow transition to a low-carbon economy.
- Share of renewable energy increases (from 14% in 2017) to 25% in 2050.
- Energy intensity improves by 30% till 2050.
- The default rate on corporate loans is around 4% till 2050.
Validation

Auto-correlation: output

-1.0

-0.5

0.0

0.5

1.0

-10  -5   0   5    10

Lag

Simulated output

Observed output
Green finance policies

• Suppose that in 2022 central banks around the globe announce that they will purchase 25% of the outstanding **green bonds** and they commit themselves that they will keep the same share of the green bond market over the next decades.

• Suppose also that in 2022 **green differentiated capital requirements** are introduced in two alternative forms:
  1. ‘Green supporting factor’: the risk weight on green loans declines by 25 percentage points
  2. ‘Brown penalising factor’: the risk weight on brown loans increases by 25 percentage points
Suppose that in 2022 green fiscal policies are introduced in the following ways:

1. **Carbon tax**: The carbon tax increases to 16 US dollars per tonne of CO₂ (this corresponds to 80 US dollars for the emissions currently covered by a carbon pricing scheme).

2. **Green public subsidies**: The green public subsidies provided by the government increases from 28% to 60% (as a proportion of green investment).

3. **Green public investment**: The green investment of the government increases from 0.25% to 1% (as a proportion of GDP).
Green finance and fiscal policies (isolated)

Atmospheric temperature

Temperature (°C above pre-industrial)

Year

Baseline
Green finance policies
Green fiscal policies
Green finance and fiscal policies (combined)

Atmospheric temperature

- Baseline
- Green finance and fiscal policies

Temperature (°C above pre-industrial)

Year

2017 2030 2040 2050 2060 2070 2080 2090 2100
Outline

1. Features of SFC models
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6. Conclusion
SFC models constitute a flexible tool for analysing complex issues that involve an active role of finance.

They have the capability of forming a solid alternative to the DSGE models.

More progress needs to be made in the way that these models are calibrated, validated and simulated.
• Many important **ecological aspects** have not yet been incorporated into SFC models (e.g. biodiversity, water scarcity).
• The **distributional aspects** of environmental policies have only partially been investigated.
• The implications of the **circular economy** and **degrowth** are still under-researched.
• The role of **power** is basically taken into account only as an exogenous factor.