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DEALING WITH FORWARD-LOOKING EXPECTATIONS AND POLICY RULES IN QUANTIFYING THE CHANNELS OF TRANSMISSION OF MONETARY POLICY

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Abstract

The issue of appraising the transmission process through which monetary policy affects the economy is receiving wider and increasing attention. In Europe, much of the interest in the effects of monetary policy is arguably a reflection of the introduction of the single currency: to the extent that transmission mechanism differ significantly across euro area countries, heterogenous responses of economic activity and prices to the policy instrument should be expected, an occurrence whose policy implications are of major relevance. To gain some insight into the likely causes of those differences recent studies have attempted to identify and assess separately the channels of transmission of monetary policy.

This paper proposes a simple methodology to quantify separately the different parts of the overall impulse response that are transmitted through the various mechanisms at play in a model of the economy. It is shown that, under the maintained assumption of linearity, the decomposition of the effects of monetary policy into a number of channels delivered by our approach is exact (i.e., it leaves no unexplained residual). This conclusion holds regardless of the nature of the expectation formation mechanism and the way in which policy decisions are modelled.

The features of the proposed approach are illustrated with an empirical application, using a model that features two distinct transmission channels and assumes rational expectations and a monetary policy reaction rule. We show that our approach produces an exact decomposition of the effects of a monetary policy shock. Moreover, and perhaps more interestingly, our approach gives a deeper insight than do standard impulse responses into the specific features of the model that are most relevant in shaping its observed reaction to the shock.

JEL classification: E17, E52.

Keywords: monetary policy transmission channels, decomposition.

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Contents

1. Introduction[1]

The issue of appraising the transmission process through which monetary policy affects the economy is receiving wider and increasing attention – as testified by the number of papers recently written on the subject – suggesting that, while nearly as old an issue as macroeconomics itself, the effects of monetary policy on the economy are far from being fully understood. For instance, how far the differences in financial structure and sectoral composition can go in explaining the differences in the transmission mechanisms across countries is a question on which full light has not yet been shed.

In Europe, much of the interest in the effects of monetary policy on output and inflation is arguably a reflection of the introduction of the single currency in January 1999. Indeed, to the extent that significant differences persist among the economies of the euro area, the single monetary policy instrument may induce heterogenous responses of economic activity and prices across countries. It is thus of the utmost importance to identify any such differences and to detect the features of the economy that may account for those differences. To this end it may be helpful to identify the various channels of transmission through which monetary policy exerts its influence on demand, output and prices, and to quantify the empirical relevance of those channels in the euro area economies. The transmission channels that the literature assumes to be of relevance are typically a sub-set of the following:

A. cost of capital
B. income-cash/flow
C. wealth
D. exchange rate
E. expectations
F. credit
G. holdings of real money balances.

In this paper we present a simple approach to decompose the overall response of an estimated (or calibrated) model to a shock into the contributions associated with a number

[1] Helpful comments by the participants in the workshop "Macroeconomic Modelling Advances", ECB, Frankfurt, July 2001, and in the 7th Annual Conference of the Society for Computation Economics, Yale, June 2001 are gratefully acknowledged. The usual disclaimer applies.

of distinct channels in such a way that the sum of those contributions leaves no unexplained residual. We consider a general linear model featuring simultaneity and dynamics and allow for the possibility that expectations are forward-looking and policy responds to the state of the economy (past, current or expected). While we explicitly consider the case of a monetary policy shock, it will be clear from the discussion that our approach can be used to decompose the effects of shocks of a different nature as well.

Our approach builds on, and further develops, a proposal originally put forward by Mauskopf and Siviero (1994) and extensively used in BIS (1995) and van Els *et al.* (2001), collecting the empirical analyses conducted by a number of central banks using a wide range of models. The proposal presented in Mauskopf and Siviero (1994) was not formally proved to deliver an exact decomposition of the effects of a shock and was only shown to work in the case of a specific linear, backward-looking model with no policy reaction function. A few questions thus naturally arise, namely what are the properties of the approach and whether it remains reliable if any of the conditions underlying the example in Mauskopf and Siviero (1994) are violated.

We first re-examine the basic case[2] and show that the concern raised by some authors, i.e. that simultaneity would prevent the decomposition from being accurate, is not justified, in that the approach is guaranteed to result in a zero discrepancy between the overall effect and the sum of the effects that are associated with the various channels of transmission. This is no longer true, unsurprisingly, if the assumption of linearity is relaxed but still holds whatever the assumptions concerning expectations formation and the monetary policy rule.

The paper is structured as follows. In Section 2 we describe the issue and introduce some notation. Section 3 briefly reviews the results in Mauskopf and Siviero (1994), showing that, with a backward-looking model and no state-contingent policy, the overall effect of a monetary shock can be easily decomposed into channels using a set of appropriately designed simulations. In each of these simulations the monetary policy shock is only allowed to transit through one single channel; however, the proposed approach is so designed that the full simultaneous structure of the model is retained in each simulation. With a linear model, the decomposition is exact and the sum of the effects that transit through each individual

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[2] The basic case refers to a model which is linear, backward-looking and with no in-built policy reaction function built in.

transmission channel exactly equals the overall effect. Sections 4 and 5 show that the accuracy of the decomposition does not in any way depend upon the assumptions one makes concerning the policy reaction function and the mechanism of expectations formation. More specifically, Section 4 tackles the issues that arise if the model also includes a monetary policy rule (so that a monetary policy shock no longer corresponds to a shock to the policy rate but rather to its discretionary component, i.e., to the error term in the policy rule). In this case an exact decomposition is, apparently, no longer possible: if the approach described in Section 3 is used "as is", then one is left with an unexplained residual. Intuitively, it is so because in this case one is effectively shocking only the discretionary component of monetary policy; however, the approach described in Section 3 cannot distinguish between the discretionary and the endogenous components. The solution to this problem is in fact rather straightforward. The results are independent of whether the policy rule is of a purely backward-looking nature or may depend on contemporaneous variables as well. Section 5 considers the case of forward-looking (or, more precisely, model-consistent) expectations. The approach of Mauskopf-Siviero (1994) is shown to work accurately even in this case provided that the maintained assumption of linearity holds. Section 6 presents an empirical application: the approach proposed in Sections 3-5 is used to decompose the effects of a monetary policy shock in a small-size, forward-looking model of the US economy. The model, proposed in Ireland (2000), allows real money balances to have a direct impact on both aggregate demand and supply and hence includes a second channel, in addition to the interest rate effect on consumer spending, through which monetary policy impulses are transmitted. In line with the theoretical results in the paper, we find that, in the linearised version of the model, an exact decomposition is feasible and show that the separate identification of the interest rate and money channels contributes to highlight relevant aspects of the transmission mechanism which are usually sidestepped. The effects of non linearities are briefly tackled in Section 7. Rather unsurprisingly, as soon as the assumption of linearity is dropped, all the clear-cut conclusions reached in the preceding sections collapse. We argue, however, that the approach is likely to remain reliable for most practical purposes, and sketch a few ways to cope with non linearity. Section 8 concludes.

2. The issue and some notation

Let us assume that an empirical model (either estimated or calibrated) is used in order to appraise the effects of monetary policy on the economy; let us further assume that a separate quantification of the effects that are transmitted through each individual channel is also sought.[3]

Our assumptions regarding the model are very general in that we allow for the existence of interactions among the various channels (i.e., simultaneity),[4] as well as for both backward- and forward-looking expectation formation mechanisms; in addition, the model may or may not include a monetary policy reaction function. For the time being, we assume the model to be linear, so that its deterministic block (to be used in simulation) may be written, without loss of generality, as follows:

$$(1) \qquad \begin{bmatrix} \underline{0}_n \\ \Delta_t \end{bmatrix} = \begin{bmatrix} A_0 & \underline{\beta}_0 \\ \underline{\gamma}_0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \underline{y}_t \\ i_t \end{bmatrix} + \begin{bmatrix} A_1 & \underline{\beta}_1 \\ \underline{\gamma}_1 & \rho_1 \end{bmatrix} \cdot \begin{bmatrix} \underline{y}_{t-1} \\ i_{t-1} \end{bmatrix} + \begin{bmatrix} A_2 & \underline{\beta}_2 \\ \underline{\gamma}_2 & 0 \end{bmatrix} \cdot \begin{bmatrix} \underline{y}^e_{t+1} \\ i^e_{t+1} \end{bmatrix} + \begin{bmatrix} \Phi \\ \underline{\psi} \end{bmatrix} \cdot \underline{x}_t$$

where:

$\underline{y}_t$ is an $(n \times 1)$ vector of endogenous variables;

$\underline{x}_t$ is an $(m \times 1)$ vector of exogenous variables;

i_t is the policy interest rate (exogenous if $\underline{\gamma}_0 = \underline{\gamma}_1 = \underline{\gamma}_2 = \underline{0}_n$, $\rho_1 = 0$ and $\underline{\psi} = \underline{0}_m$; endogenous otherwise; note that, in this model, endogenous monetary policy may respond to the past, current and future expected states of the economy or to a mixture of the three, depending on the restrictions imposed on the policy reaction funtion);

Δ_t is a shock to the discretionary component of (endogenous) monetary policy;

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[3] Evaluating the effects of monetary policy that transit through the various transmission channels was one of the goals of the collective exercise whose results were published in BIS (1995). Specifically, decomposing the overall effects of monetary policy into the individual contributions of a number of transmission channels was meant to cast light on the issue of identifying the structural determinants of the differences in the timing and intensity with which output and prices react to a monetary policy shock in a number of countries. Specifically, the BIS (1995) study sought to identify the linkages between the financial structures in the various countries and the corresponding pattern of responses of GDP and prices to a change in the policy interest rate. For a similar approach see also the more recent empirical results reported in van Els *et al.* (2001).

[4] This feature is worth emphasising; our findings below imply that the accuracy of the decomposition of the transmission channels is in no way hampered by simultaneity.

the superscript e denotes expectations; i.e., $z^e_{t+j} = E(z_{t+j}|\Omega_{t-k})$, where Ω_{t-k} is the information set as of time $t-k, k \geq 0$;

A_0, A_1 and A_2 are $(n \times n)$ matrices of (estimated or calibrated) parameters;

Φ is an $(n \times m)$ matrix of parameters;

$\underline{\psi}$ is a $(1 \times m)$ vector of parameters in the monetary policy reaction function;

$\underline{\beta}_0$, $\underline{\beta}_1$ and $\underline{\beta}_2$ are $(n \times 1)$ vectors of parameters, denoting the direct impact of the policy instrument on the endogenous variables;

$\underline{\gamma}_0$, $\underline{\gamma}_1$ and $\underline{\gamma}_2$ are $(1 \times n)$ vectors of parameters in the monetary policy reaction function, describing how policy responds to the state of the economy;

ρ_1 is the autoregressive parameter in the monetary policy reaction function.

To clarify the focus of the paper, let us first address the case in which no policy reaction function is postulated so that $\underline{\gamma}_0 = \underline{\gamma}_1 = \underline{\gamma}_2 = \underline{0}_n$, $\rho_1 = 0$ and $\underline{\psi} = \underline{0}_m$; let us further assume that there are no forward-looking expectations in the model so that, in addition to the restrictions above, $A_2 = [0]$ and $\underline{\beta}_2 = \underline{0}_n$. Model (1) simplifies to:

$$A_0\underline{y}_t + A_1\underline{y}_{t-1} + \underline{\beta}_0 i_t + \underline{\beta}_1 i_{t-1} + \Phi\underline{x}_t = \underline{0} \tag{2}$$

The corresponding reduced form is thus given by:

$$\begin{aligned} \underline{y}_t &= -A_0^{-1}A_1\underline{y}_{t-1} - A_0^{-1}\underline{\beta}_0 i_t - A_0^{-1}\underline{\beta}_1 i_{t-1} - A_0^{-1}\Phi\underline{x}_t \\ &= \Pi_0\underline{y}_{t-1} + \underline{\pi}_1 i_t + \underline{\pi}_2 i_{t-1} + \Pi_3\underline{x}_t \end{aligned} \tag{3}$$

where: Π_0 is an $(n \times n)$ matrix, $\underline{\pi}_1$ and $\underline{\pi}_2$ are $(n \times 1)$ vectors and Π_3 is an $(n \times n)$ matrix.

The overall effects of monetary policy on the macroeconomy may be computed easily on the basis of the reduced form:

$$\begin{aligned} \frac{\partial \underline{y}_t}{\partial i_t} &= \underline{\pi}_1 \\ \frac{\partial \underline{y}_{t+1}}{\partial i_t} &= \Pi_0\underline{\pi}_1 + \underline{\pi}_2 \\ \frac{\partial \underline{y}_{t+2}}{\partial i_t} &= \Pi_0(\Pi_0\underline{\pi}_1 + \underline{\pi}_2) \\ &\ldots \end{aligned} \tag{4}$$

The issue we tackle in this paper is: can the empirical relevance of the monetary policy transmission channels be separately quantified in such a way that the sum of the channels' individual contributions matches the overall effect of monetary policy on the economy?

Isolating the direct effects only does not, in general, fulfil the requirement that the sum of individual effects matches the overall effect (for instance $\underline{\pi}_1 \neq \underline{\beta}_0$, unless $A_0 = I$).

The experiments in Mauskopf (1990) did not stop at considering the sole direct effects. The approach consisted in identifying a set of sub-blocks in the Fed's MPS model, designed in such a way that each of them included just one transmission mechanism of monetary policy, possibly with a number of feedbacks; the sub-blocks were chosen in such a way that the mechanisms activated by the various channels did not interfere with each other; the sub-blocks were then simulated one at a time. While allowing for the possibility of within-block simultaneity, that approach neglected by design any simultaneous interactions among sub-blocks. As a result, one was left with an unexplained residual, being the difference between the overall effect and the sum of the effects associated with all the individual channels.

The fact that the sum of individual effects does not match the overall effect of a monetary policy shock on the economy might not represent such a serious drawback if it were the case that one could still correctly estimate the relative size of the effects associated with the various channels. Unfortunately, that approach (referred to below as the "isolated sub-blocks" approach below) will in general result in a wrong ranking of the channels of transmission of monetary policy (see Sections 3 and 6 below). Indeed, for some of the experiments presented in BIS (1995) (see also Mauskopf-Siviero (1994)) the approach just described resulted in an incorrect ranking of the various channels.

An approach designed to decompose the overall effects in such a way as to leave no unexplained residuals (provided that one uses a linear model) was proposed in Mauskopf-Siviero (1994). That approach may be briefly described as follows:

(i) identify all channels whose empirical relevance is to be quantified; let us assume that n separate channels are identified (i.e., as many as the total number of equations in the model);[5]

[5] The possibility that there are fewer channels than the number of endogenous variables in the model can be easily dealt with (see the next footnote). The simplified description given in the text ignores the possibility that the point at which the various channels separate does not correspond to a "point of entry" of the policy variable

(ii) for each channel, introduce a dummy variable with values 0 or 1 ("flag" variables). There will then be as many flag variables as the number of channels. The flag variable associated with channel j will be set equal to 1 only in the simulation aimed at isolating the effects that transit through the j-th channel; it will be set equal to 0 in all other simulations;

(iii) replace the policy variable, wherever it appears in the model, with an expression given by the sum of two components: (i) the shocked policy variable, multiplied by the corresponding flag variable; (ii) the baseline policy variable, multiplied by one minus the flag variable;

(iv) run n simulations; in each of them only one flag variable is equal to 1, whereas all others are set to zero. Hence, the endogenous variables are left free to interact in all simulations so that simultaneity is fully taken into account; however, each endogenous variable can directly respond to the policy shock only in the simulation in which the corresponding flag variable is active.

The approach described above amounts to simulating n times the following modified version of model (2):

$$\underline{0} = A_0 \underline{y}_t + A_1 \underline{y}_{t-1} + \sum_{j=1} \underline{\beta}_0 (f_j \cdot i_t^S + (1 - f_j) \cdot i_t^B) + \sum_{j=1} \underline{\beta}_1 (f_j \cdot i_{t-1}^S + (1 - f_j) \cdot i_{t-1}^B) + \Phi \underline{x}_t \tag{5}$$

where each flag f_j is a scalar with $f_j = 1$ only in the simulation aimed at quantifying the effects of the j-th channel, whereas it is zero otherwise;[6] the superscript S identifies shocked values of the policy instrument; the superscript B identifies baseline values of the latter.

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in the model. One may think, for instance, of the following case: the policy interest rate only enters the long-term interest rate equation; long-term rates affect the economy through several distinct channels. The approach sketchily described in the text does not take such a possibility into account. Such an occurrence may, however, be easily dealt with (it does not differ from the case of an endogenously generated policy instrument; see below).

[6] Obviously, several "points of entry" of the policy interest rate may belong to the same channel of transmission (one may think, for instance, of a model in which a number of different investment components are separately modelled in distinct equations: the effects that transit through those components should all be attributed to the same channel, i.e., the "cost of capital" channel). Thus, the number of channels may be substantially lower than n, in which case the various flags fl_J will be given by the (mutually exclusive) unions of a set of "elementary" flags f_j.

It is convenient to rewrite the model, inclusive of the newly introduced flag variables, as follows:

$$
\begin{aligned}
(6) \qquad \underline{0} &= A_0 \underline{y}_t + A_1 \underline{y}_{t-1} + \sum_{j=1} B_0 (F_j \cdot \underline{i}_t^S + (I_n - F_j) \cdot \underline{i}_t^B) \\
&+ \sum_{j=1} B_1 (F_j \cdot \underline{i}_{t-1}^S + (I_n - F_j) \cdot \underline{i}_{t-1}^B) + \Phi \underline{x}_t
\end{aligned}
$$

where F_j is now an $(n \times n)$ matrix, with $F_j(k,l) = 1$ if $k = l = j$, $F_j(k,l) = 0$ otherwise; clearly, $\sum_{j=1}^{n} F_j = I_n$; B_0 and B_1 are $(n \times n)$ matrices, having the elements of the vectors $\underline{\beta}_0$ and $\underline{\beta}_1$ respectively along their main diagonals, i.e., $B_j = diag[\underline{\beta}_j]$; $\underline{i}_t^S$ and $\underline{i}_t^B$ are $(n \times 1)$ vectors, whose elements are identically equal to i_t^S and i_t^B respectively, i.e., $\underline{i}_t^J = \underline{1} \cdot i_t^J$, where $\underline{1}$ is an $(n \times 1)$ vector of 1's.

Mauskopf-Siviero (1994) proposed the approach oulined above, suggesting that it provides an exact decomposition (i.e., it results in a zero unexplained residual) of the overall effects of monetary policy on the economy (under the assumption that the model is linear), but did not formally prove that claim (although it was shown to hold in a case of a small, simple model). Jahnke-Reimer (1995) argued that simultaneity would prevent that approach from providing an exact decomposition:"...it is, admittedly, a disadvantage in this approach that in interdependent models the sum of the partial effects does not necessarily result in the overall effect...". Similarly, Boeschoten-van Els (1995) expressed the fear that, "...due to the interaction between different channels, the decomposed contributions do not necessarily add up to the simulated total effect." Sgherri (1999) suggested that the approach described above would not be appropriate if expectations were forward-looking, stating that, while "with linear backward-looking macroeconomic models the decomposition of a simulation into contributing channels is unique and independent of the order in which the decomposition is carried out, this is not true [...] when the expectations formation is explicitly forward-looking." It is worth remarking that not only the model in Sgherri (1999) is forward-looking, but it also allows for the monetary authority to react to the state of the economy.

In the following sections we tackle these issues in turn.

3. The linear backward-looking case

The linear backward-looking case can be dealt with straightforwardly.

Instead of simulating model (6) the multipliers can be computed analytically using the following model:

$$A_0\underline{y}_t + A_1\underline{y}_{t-1} + \sum_{j=1} B_0(F_j \cdot \underline{i}_t) + \sum_{j=1} B_1(F_j \cdot \underline{i}_{t-1}) + \Phi\underline{x}_t = \underline{0} \tag{7}$$

For each individual channel j its effect can be quantified by setting, in the corresponding flag matrix F_j, $F_j(j,j) = 1$, while setting all other elements, as well as all those of any other flag matrix, equal to zero. Model (7) may thus be thought of as the sum of n different models, one for each individual channel. For the j-th model, corresponding to the j-th channel, we may compute the following reduced form:

$$\underline{y}_t^{\text{channel } j} = \Pi_0\underline{y}_{t-1} + \Pi_1 F_j \underline{i}_t + \Pi_2 F_j \underline{i}_{t-1} + \Pi_3 \underline{x}_t \tag{8}$$

where Π_0 and Π_3 are the same matrices as defined above and Π_1 and Π_2 are $(n \times n)$ matrices, whose definition is obvious.

The effects of monetary policy that transit through channel j may thus be computed as follows:

$$\begin{aligned}
\frac{\partial \underline{y}_t^{\text{channel } j}}{\partial i_t} &= \Pi_1 F_j \cdot \underline{1} \\
\frac{\partial \underline{y}_t^{\text{channel } j}}{\partial i_{t-1}} &= [\Pi_0\Pi_1 F_j + \Pi_2 F_j] \cdot \underline{1} \\
\frac{\partial \underline{y}_t^{\text{channel } j}}{\partial i_{t-2}} &= [\Pi_0(\Pi_0\Pi_1 F_j + \Pi_2 F_j)] \cdot \underline{1} \\
&\dots
\end{aligned} \tag{9}$$

Hence, the sum of all individual (impact and interim) multipliers associated with the different transmission channel effects is given by:

$$\begin{aligned}
\sum_{j=1} \frac{\partial \underline{y}_t^{\text{channel } j}}{\partial i_t} &= \sum_{j=1} \Pi_1 F_j \cdot \underline{1} = \Pi_1 \cdot (\sum_{j=1} F_j) \cdot \underline{1} = \Pi_1 \cdot \underline{1} = \underline{\pi}_1 \\
\sum_{j=1} \frac{\partial \underline{y}_t^{\text{channel } j}}{\partial i_{t-1}} &= \sum_{j=1} (\Pi_0\Pi_1 F_j \cdot \underline{1} + \Pi_2 F_j \cdot \underline{1}) = \Pi_0\underline{\pi}_1 + \underline{\pi}_2 \\
\sum_{j=1} \frac{\partial \underline{y}_t^{\text{channel } j}}{\partial i_{t-2}} &= \sum_{j=1} \Pi_0(\Pi_0\Pi_1 F_j \cdot \underline{1} + \Pi_2 F_j \cdot \underline{1}) = \Pi_0(\Pi_0\underline{\pi}_1 + \underline{\pi}_2) \\
&\dots
\end{aligned} \tag{10}$$

since, with $\underline{\pi}_1$ and $\underline{\pi}_2$ defined as in the previous section, $\Pi_j \cdot \underline{1} = \underline{\pi}_j$, $j = 1, 2$.

Therefore, the sum of the effects that transit through the individual channels exactly matches the overall effect that can be estimated from the reduced form of the whole model (compare the expressions above with those provided in Section 2). Hence, at least in the case of a linear backward-looking model with no policy reaction function, simultaneity does not prevent the "flag approach" from delivering an accurate decomposition of the impact of monetary policy on the economy.

One may easily build examples in which the "isolated sub-block" approach described earlier would deliver a wrong ranking of the effects associated with the various channels. Consider, e.g., the following two-equation model:

$$\begin{pmatrix} 1 & a_{12} \\ a_{21} & 1 \end{pmatrix} \cdot \begin{pmatrix} y_{1t} \\ y_{2t} \end{pmatrix} = \begin{pmatrix} b_1 \\ b_2 \end{pmatrix} \cdot x_t \tag{11}$$

where we assume $a_{12}, a_{21} < 1$.

The multipliers are thus given by:

$$\begin{pmatrix} \frac{\partial y_{1t}}{\partial x_t} \\ \frac{\partial y_{2t}}{\partial x_t} \end{pmatrix} = \begin{pmatrix} \frac{b_1 - a_{12} b_2}{1 - a_{12} a_{21}} \\ \frac{b_2 - a_{21} b_1}{1 - a_{12} a_{21}} \end{pmatrix} \tag{12}$$

Following the "isolated sub-blocks" approach (given that this model has only two channels, the approach amounts to computing the direct effects associated with each channel), one gets the following decomposition:

$$\begin{pmatrix} \frac{\partial y_{1t}}{\partial x_t} \\ \frac{\partial y_{2t}}{\partial x_t} \end{pmatrix}_{\text{isb}}^{\text{channel 1}} = \begin{pmatrix} b_1 \\ 0 \end{pmatrix}, \quad \begin{pmatrix} \frac{\partial y_{1t}}{\partial x_t} \\ \frac{\partial y_{2t}}{\partial x_t} \end{pmatrix}_{\text{isb}}^{\text{channel 2}} = \begin{pmatrix} 0 \\ b_2 \end{pmatrix} \tag{13}$$

As expected, the two effects do not, in general, sum to the total (eq. (12)).

If the "flag" approach is adopted, the following channel decomposition is obtained:

$$\begin{pmatrix} \frac{\partial y_{1t}}{\partial x_t} \\ \frac{\partial y_{2t}}{\partial x_t} \end{pmatrix}_{\text{fl}}^{\text{channel 1}} = \begin{pmatrix} \frac{b_1}{1 - a_{12} a_{21}} \\ \frac{-a_{21} b_1}{1 - a_{12} a_{21}} \end{pmatrix}, \quad \begin{pmatrix} \frac{\partial y_{1t}}{\partial x_t} \\ \frac{\partial y_{2t}}{\partial x_t} \end{pmatrix}_{\text{fl}}^{\text{channel 2}} = \begin{pmatrix} \frac{-a_{12} b_2}{1 - a_{12} a_{21}} \\ \frac{b_2}{1 - a_{12} a_{21}} \end{pmatrix} \tag{14}$$

In this case, the sum of the effects associated with the two channels matches the total.

Moreover, there is no guarantee that the two approaches deliver the same ranking of the transmission channels unless some conditions are satisfied (more generally, the relative size of the effects would probably be wrongly estimated by the isolated sub-block approach). If $-a_{12}b_2 > b_1 > 0$ (so that the flag approach indicates that “channel 2” is quantitatively more relevant than ”channel 1” as far as the effects on y_{1t} are concerned) the isolated sub-block approach would result in a reverse ranking of the two channels. In BIS (1995) and Mauskopf-Siviero (1994), several simulation experiments do indeed show that incorrect ranking of the transmission channels is by no means an exception but, on the contrary, tends to occur frequently in empirical applications.

4. Dealing with policy reaction functions

Let us now consider a model that includes a policy reaction function. For simplicity, let us for the time being ignore the possibility of forward-looking expectations. Hence, the model we consider in this section may be written as follows:

$$\text{(15)} \qquad \begin{pmatrix} A_0 & \underline{\beta}_0 \\ \underline{\gamma}_0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \underline{y}_t \\ i_t \end{pmatrix} + \begin{pmatrix} A_1 & \underline{\beta}_1 \\ \underline{\gamma}_1 & \rho_1 \end{pmatrix} \cdot \begin{pmatrix} \underline{y}_{t-1} \\ i_{t-1} \end{pmatrix} + \begin{pmatrix} \Phi \\ \underline{\psi} \end{pmatrix} \cdot \underline{x}_t = \begin{pmatrix} \underline{0} \\ \Delta_t \end{pmatrix}$$

As in Section 2, let us rewrite the model above in the following, equivalent way:

$$\text{(16)} \qquad \begin{pmatrix} A_0 & B_0 \\ \Gamma_0 & I_n \end{pmatrix} \cdot \begin{pmatrix} \underline{y}_t \\ \underline{i}_t \end{pmatrix} + \begin{pmatrix} A_1 & B_1 \\ \Gamma_1 & P_1 \end{pmatrix} \cdot \begin{pmatrix} \underline{y}_{t-1} \\ \underline{i}_{t-1} \end{pmatrix} + \begin{pmatrix} \Phi \\ \Psi \end{pmatrix} \cdot \underline{x}_t = \begin{pmatrix} \underline{0} \\ \underline{\Delta}_t \end{pmatrix}$$

where B_0, B_1, $\underline{i}_t$ and $\underline{i}_{t-1}$ are defined as in Section 2, $\Gamma_j = [\gamma_j'|...|\gamma_j']'$, $j = 0, 1$, is an $(n \times n)$ matrix, $P_1 = \rho_1 I_n$, $\Psi = [\psi'|...|\psi']'$ is an $(n \times m)$ matrix, $\underline{\Delta}_t = [\Delta_t, ..., \Delta_t]'$ is an $(n \times 1)$ vector.

The reduced form of the model above is given by:

$$\text{(17)} \qquad \begin{aligned} \begin{pmatrix} \underline{y}_t \\ \underline{i}_t \end{pmatrix} = & - \begin{pmatrix} A_0 & B_0 \\ \Gamma_0 & I_n \end{pmatrix}^{-1} \cdot \begin{pmatrix} A_1 & B_1 \\ \Gamma_1 & P_1 \end{pmatrix} \cdot \begin{pmatrix} \underline{y}_{t-1} \\ \underline{i}_{t-1} \end{pmatrix} \\ & - \begin{pmatrix} A_0 & B_0 \\ \Gamma_0 & I_n \end{pmatrix}^{-1} \cdot \begin{pmatrix} \Phi \\ \Psi \end{pmatrix} \cdot \underline{x}_t + \begin{pmatrix} A_0 & B_0 \\ \Gamma_0 & I_n \end{pmatrix}^{-1} \cdot \begin{pmatrix} \underline{0} \\ \underline{\Delta}_t \end{pmatrix} \end{aligned}$$

Let us consider, for the time being, the impact multiplier (i.e., the immediate reaction of the economy to a change in the *discretionary* component of monetary policy); using the result for the inverse of a partitioned matrix one gets:

$$\text{(18)} \qquad \frac{\partial \underline{y}_t}{\partial \Delta_t} = A_0^{-1} B_0 (I_n - \Gamma_0 A_0^{-1} B_0)^{-1} \cdot \underline{1}$$

where $\underline{1}$ is an $(n \times 1)$ vector of 1's.

It may be easily checked that the system of flags described in Section 3 above does not work if used "as is". If the flag matrices are used to include or to "include out" (as Sam Goldwyn would put it) the direct impact of the policy instrument i_t on the various endogenous variables, then the sum of the effects associated with the various channels will not match the overall effect. To see this, let there be n flag matrices F_j defined as in Section 2; let us now apply the flag matrices to the B_j's matrices (as in Section 2) to get a collection of n models, the j-th of which is given by:[7]

$$(19)\qquad \begin{bmatrix} A_0 & B_0F_j \\ \Gamma_0 & I_n \end{bmatrix} \cdot \begin{bmatrix} \underline{y}_t \\ \underline{i}_t \end{bmatrix} + \begin{bmatrix} A_1 & B_1F_j \\ \Gamma_1 & P_1 \end{bmatrix} \cdot \begin{bmatrix} \underline{y}_{t-1} \\ \underline{i}_{t-1} \end{bmatrix} + \begin{bmatrix} \Phi \\ \Psi \end{bmatrix} \cdot \underline{x}_t = \begin{bmatrix} \underline{0} \\ \underline{\Delta}_t \end{bmatrix}$$

The impact multiplier for the j-th channel is thus:

$$(20)\qquad \frac{\partial \underline{y}_t^{\text{channel } j}}{\partial \Delta_t} = A_0^{-1}B_0F_j(I_n - \Gamma_0A_0^{-1}B_0F_j)^{-1} \cdot \underline{1}$$

Clearly, the sum of the effects associated with the various channels:

$$(21)\qquad \sum_{j=1} \frac{\partial \underline{y}_t^{\text{channel } j}}{\partial \Delta_t} = \sum_{j=1} [A_0^{-1}B_0F_j \cdot (I_n - \Gamma_0A_0^{-1}B_0F_j)^{-1} \cdot \underline{1}]$$

will, in general, differ from the overall effect, hence leaving an unexplained residual; this is so because of the non-linear transformation implied by the inversion, for each channel, of a different (function of the) corresponding simultaneous block.

If $\Gamma_0 = [0]$ but $\Gamma_1 \neq [0]$ (i.e., the policy reaction function is purely backward-looking), then the impact multiplier would still be exactly decomposable; however, the decomposition would turn out to be inaccurate as soon as the multipliers at the following periods were considered. It may also be easily checked that if $\Gamma_0 = \Gamma_1 = [0]$ (which amounts to assuming no state-contingent policy reaction function, i.e., the same model as in Section 3), eq. (21) is the same as eq. (18) (i.e., the decomposition would be accurate).

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[7] As anticipated in a previous footnote, a model that includes a policy reaction function is a special case of a model in which the transmission channels do not separate at a "point of entry" of the policy variable. In eq. (15) in the text, simply define Δ_t to be the policy interest rate and i_t to be the long-term interest rate, so that the last equation in the model is no longer to be interpreted as the monetary policy reaction function, but rather as a term-structure equation. This means that the transmission channels become separately identified only at some point iside the simultaneous block of the model. Thus, the approach outlined in this section is also appropriate in the case of a model in which the transmission channels do no separate at a "point of entry" of the policy variable.

The remark above suggests that the problem with using the flags in the same way as outlined in Sections 2 and 3 rests precisely with the presence of a policy reaction function: as soon as the latter comes into play (with a backward-looking policy rule this happens in period 2) the approach collapses.

In the light of these remarks, one's intuition is that the source of trouble lies in the nature of the shock. Specifically, in this case the overall effect measures the consequences of a shock to the discretionary component of the policy variable only. On the contrary, the approach outlined earlier in this section is such that, when a channel is alternatively included or excluded from the model, *both* the discretionary component of policy *and* the response implied by the presence of a policy reaction function are *jointly either included or excluded*. It is rather obvious that this cannot be a promising approach.

The foregoing discussion suggests the following intuitive and simple solution: given that the genuine exogenous variable whose effects are to be separately attributed to the various transmission channels is now Δ_t rather than i_t, it is natural to apply the system of flags to Δ_t itself. To this end, let us consider a collection of n "flagged" models, the j-th of them being as follows:

$$\begin{pmatrix} A_0 & B_0 \\ \Gamma_0 & I_n \end{pmatrix} \cdot \begin{pmatrix} \underline{y}_t \\ \underline{i}_t \end{pmatrix} + \begin{pmatrix} A_1 & B_1 \\ \underline{\gamma}_1 & P_1 \end{pmatrix} \cdot \begin{pmatrix} \underline{y}_{t-1} \\ \underline{i}_{t-1} \end{pmatrix} + \begin{pmatrix} \Phi \\ \Psi \end{pmatrix} \cdot \underline{x}_t = \begin{pmatrix} 0 & 0 \\ 0 & F_j \end{pmatrix} \cdot \begin{pmatrix} \underline{0} \\ \underline{\Delta}_t \end{pmatrix} \tag{22}$$

where F_j is defined in the usual way.

Each model j may be used to quantify the multipliers associated with the j-th channel; for instance, the impact multiplier is given by:

$$\frac{\partial \underline{y}_t^{\text{channel } j}}{\partial \Delta_t} = A_0^{-1} B_0 (I_n - \Gamma_0 A_0^{-1} B_0)^{-1} F_j \cdot \underline{1}, \qquad j = 1, ..., n \tag{23}$$

Therefore, the sum of the impact effects that transit through all channels:

$$\sum_{j=1} \frac{\partial \underline{y}_t^{\text{channel } j}}{\partial \Delta_t} = A_0^{-1} B_0 (I_n - \Gamma_0 A_0^{-1} B_0)^{-1} \Big(\sum_{j=1} F_j\Big) \cdot \underline{1} \tag{24}$$

$$= A_0^{-1} B_0 (I_n - \Gamma_0 A_0^{-1} B_0)^{-1} \cdot \underline{1} \tag{25}$$

exactly matches the overall effect (see eq. (18)). Tedious algebra shows that the equality holds for all interim multipliers.

To summarize the results so far, whether or not the (linear) model one is using includes a monetary policy reaction function, a proper approach may be designed that exactly decomposes the overall effects into a number of transmission channels.

5. The linear forward-looking case

Let us now maintain the assumption that monetary policy impulses are measured by the discretionary component of the reaction function, but relax the restriction that the model does not include forward-looking expectations

A simplified version of the general model (1) that we consider in this paragraph is the following:

$$\underline{y}_t = A\underline{y}^e_{t+1} + D\underline{x}_t \tag{26}$$

where A and D are respectively an $n \times n$ and an $n \times m$ matrix; the $n \times 1$ vector $\underline{y}_t$ now includes the policy instrument as well. While the model above may at first appear to be overly simple, it is in fact quite general. To close the model it is then necessary to assume a generating process for the exogenous variables. The most general hypothesis is that $\underline{x}_t = \sum_{j=0}^{\infty} \Theta_j \underline{\varepsilon}_{t-j}$, where $\underline{\varepsilon}_t$ is an innovation process and $\sum_{j=0}^{\infty} |\Theta_j| < \infty$ to ensure that the process is stationary. Following Taylor (1986), the solution may be found by using the method of undetermined coefficients, which amounts to assuming for $\underline{y}_t$ an unrestricted linear process, similar to the one assumed for $\underline{x}_t$ and to solving for the unknown parameters by imposing that the assumed process solves the vector system (26). In this way, the problem of solving a stochastic difference vector equation with conditional expectations of future variables is converted into a problem of solving a deterministic dynamic system. Hence, let us start with the initial guess that $\underline{y}_t = \sum_{j=0}^{\infty} \Gamma_j \underline{\varepsilon}_{t-j}$ and, for the sake of simplicity, let us in addition assume that $\Theta_j = \Theta^j$ so as to ensure that it is possible to obtain a solution in closed form. In the general case in which no linear combination of the exogenous variables is a degenerate stochastic process the matrix Θ is full rank. Substituting the tentative solution in (26), one gets:

$$\sum_{j=0}^{\infty} \Gamma_j \underline{\varepsilon}_{t-j} = A\left(\sum_{j=1}^{\infty} \Gamma_j \underline{\varepsilon}_{t+1-j}\right) + D\left(\sum_{j=0}^{\infty} \Theta^j \underline{\varepsilon}_{t-j}\right) \tag{27}$$

which implies that:

(28) $$\Gamma_j = A\Gamma_{j+1} + D\Theta^j \qquad j = 0, 1, 2, ...$$

This is a standard deterministic first-order difference equation, whose general solution is obtained by summing the solution to the homogeneous part $\left\{\Gamma_j^H\right\}_{j=0}^{\infty}$ and the particular solution to the non-homogeneous part $\left\{\Gamma_j^P\right\}_{j=0}^{\infty}$. It is worth stressing that the model as such is undetermined: for $j = 0$ there are $2n^2$ unknowns and only n^2 equations. The necessary additional restrictions are to be found by appealing to initial conditions[8] and by requiring that the solution be stationary and unique.

The structure of the model suggests that an educated guess for $\left\{\Gamma_j^P\right\}_{j=0}^{\infty}$ is to assume that $\Gamma_j^P = \Xi\Theta^j$, with Ξ to be determined so as to satisfy eq. (28) for each value of j. For $j = 0$ eq. (28) requires that $\Xi - A\Xi\Theta = D$ and the elements of Ξ can be recovered by the relation $vec(\Xi) = (I - \Theta' \otimes A)^{-1} vec(D)$. It is worth stressing that the existence of a solution for the matrix Ξ does not hinge on the invertibility of the matrix A: all is required is that the eigenvalues of the two matrices Θ and A do not come in reciprocal pairs.

The solution to the homogeneous part of eq. (28), namely:

(29) $$\Gamma_j^H = A\Gamma_{j+1}^H,$$

is more easily found by focusing on one column at a time:

(30) $$\gamma_j = A\gamma_{j+1},$$

where γ_j is any one of the column vectors in Γ_j^H. In a given application, some elements of the vector γ_0, viz. k, will be known: these are restrictions that can be generally derived from the initial conditions for the predetemined variables. To get a unique solution we therefore need $n - k$ additional equations. These additional restrictions can be obtained by requiring that the solution for y_t be stationary. If there are exactly $n - k$ distinct roots of A which are smaller

[8] The relationship between initial and terminal conditions, the number of stable and unstable roots, and the constraints which are needed to determine the solution of the system of difference equations providing the undetermined coefficients will be made clear by means of an example.

than one in modulus, then the saddle point manifold will give the precise number of additional restrictions which are necessary for a unique solution.[9]

Under the assumption that the matrix A is non-singular,[10] that it can be diagonalized and that the system is ordered in such a way that the unstable roots come first, then (30) can be written as follows:

$$\gamma_j = H^{-1}\Lambda H\gamma_{j+1} \quad \Longleftrightarrow H\gamma_{j+1} = \Lambda^{-1}H\gamma_j \tag{31}$$

where H and Λ are respectively the matrix of eigenvectors and eigenvalues of A. Partitioning (31) according to the sequence of unstable and stable roots, one can then write:

$$\begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} \begin{pmatrix} \gamma^1_{j+1} \\ \gamma^2_{j+1} \end{pmatrix} = \begin{pmatrix} \Lambda_1^{-1} & 0 \\ 0 & \Lambda_2^{-1} \end{pmatrix} \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} \begin{pmatrix} \gamma^1_j \\ \gamma^2_j \end{pmatrix} \tag{32}$$

where Λ_1 is the diagonal matrix containing all the unstable roots. For stability we require that $H_{11}\gamma^1_1 + H_{12}\gamma^2_1 = 0$. These $n - k$ equations define the saddle point manifold and are the additional constraints which are needed for a solution. Having solved for γ_1 and the unknown elements of γ_0 we then obtain the remaining γ_i coefficients from:

$$\begin{aligned} \gamma^1_{j+1} &= -H_{11}^{-1}H_{12}\gamma^2_{j+1} \\ \gamma^2_{j+1} &= \Lambda_2^{-1}\gamma^2_j \end{aligned} \tag{33}$$

The solution of the homogeneous part is hence given by the set of matrices:

$$\Gamma^H_j = \begin{bmatrix} -H_{11}^{-1}H_{12}\Gamma^2_j \\ \Gamma^2_j \end{bmatrix} = \begin{bmatrix} -H_{11}^{-1}H_{12}\Lambda_2^{-j}\Gamma^2_0 \\ \Lambda_2^{-j}\Gamma^2_0 \end{bmatrix}, \tag{34}$$

where the matrices Γ^1_j and Γ^2_j are obtained by collecting the n vectors γ^1_j and γ^2_j respectively. The general solution $\{\Gamma_j\}$ is hence provided by the sequence $\left\{\Gamma^H_j + \Xi\Theta^j\right\}_{j=1}^{\infty}$.

Since the stochastic process $\underline{y}_t = \sum_{j=0} \Gamma_j \underline{\varepsilon}_{t-j}$ identically satisfies (26), the interim multipliers of the endogenous variables with respect to a policy shock are given by $\frac{\partial \underline{y}_t}{\partial \underline{\varepsilon}_{t-k}} = \Gamma_k$. Notice that the matrix D which premultiplies the exogenous variables (and hence the monetary

9 The classical reference for this claim is Blanchard and Kahn (1980).

10 This is by no means an irrelevant assumption. In most cases, for instance when the system (26) has a recursive structure or when the model accommodates expectations taken at different points in time, the reverse is true. This assumption is made for the sake of simplicity and will be dropped in the sequel.

shock as well) enters the particular solution linearly. Since the matrix $\Gamma_k \equiv \Gamma_k^H + \Xi\Theta^k$ is a linear function of D for any k, the channel decomposition by means of the flag method also preserves the additivity property for models with forward looking variables.

Closed-form solutions are not available for the more general case $\Theta_j \neq \Theta^j$ but it still holds true that the matrices Γ_j and Θ_j are linked by a linear relationship, as equation (28) clearly indicates.

The above demonstration relies on the invertibility of the matrix A, which turns out to be quite a restrictive assumption. The more general linear case, with unconstrained lag and lead structure and with expectations taken at different points in time, namely:

$$\underline{z}_t = \sum_{j=1} A_{j0}\underline{z}_{t-j} + \sum_{j=0}\sum_{i=1} A_{ji}E_{t-j}\underline{z}_{t+i-j} + D_z x_t,$$

may always be transformed[11], provided that the state vector is properly defined, into a multivariate second-order vector system of the following form:

$$A_0\underline{y}_t = A_1 E_t \underline{y}_{t+1} + B\underline{y}_{t-1} + Dx_t.$$

In general, the matrix A_1 is non-invertible and non-diagonalizable and the procedure outlined above to find the solution for $\underline{y}_t$ must be modified. Either the Jordan factorization or the generalized Schur decomposition must be used and equation (32) must be changed accordingly, allowing respectively for a block diagonal or a block upper triangular Λ matrix.

A bivariate example will help clarify how the recipe actually works. Let us assume that the model to be solved, which satisfies the saddle path property, is the following:

$$\begin{aligned}
\underline{z}_{1t} &= A_1 E_t \underline{z}_{1t+1} + A_2 \underline{z}_{2t} + A_3 \underline{z}_{2t-1} + \delta_1 \underline{x}_t \\
\underline{z}_{2t} &= B_1 E_t \underline{z}_{1t+1} + B_2 \underline{z}_{1t} + B_3 \underline{z}_{2t-1} + \delta_2 \underline{x}_t
\end{aligned}$$

where the $n-k\times 1$ vector $\underline{z}_{1t}$ collects the set of forward looking variables, while the $k\times 1$ vector $\underline{z}_{2t}$ includes all the predetermined variables. In matrix notation the system may expressed as follows:

$$\begin{bmatrix} I & -A_3 \\ -B_2 & -B_3 \end{bmatrix} \underline{y}_t = \begin{bmatrix} A_1 & A_2 \\ B_1 & B_3 \end{bmatrix} E_t \underline{y}_{t+1} + \begin{bmatrix} \delta_1 \\ \delta_2 \end{bmatrix} \underline{x}_t,$$

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[11] See Gourieroux and Monfort (1997).

where $\underline{y}_t = \left(\underline{z}'_{1t} \quad \underline{z}'_{2t-1} \right)'$. By inverting the matrix on the left-hand side the above expression is transformed into (26). The tentative solution for the component of the vector $\underline{y}_t$ is:

$$\begin{aligned} \underline{z}_{1t} &= \sum_{j=1} \Gamma_{1j} \underline{\varepsilon}_{t-j} \\ \underline{z}_{2t} &= \sum_{j=1} \Gamma_{2j} \underline{\varepsilon}_{t-j} \end{aligned}$$

implying that:

$$\underline{y}_t = \begin{bmatrix} \underline{z}_{1t} \\ \underline{z}_{2t-1} \end{bmatrix} = \begin{bmatrix} \Gamma_{10} \\ 0 \end{bmatrix} \underline{\varepsilon}_t + \begin{bmatrix} \Gamma_{11} \\ \Gamma_{20} \end{bmatrix} \underline{\varepsilon}_{t-1} + \begin{bmatrix} \Gamma_{12} \\ \Gamma_{21} \end{bmatrix} \underline{\varepsilon}_{t-2} + ... \ .$$

Under the assumption that $\underline{x}_t = \sum_{j=0} \Theta_j \underline{\varepsilon}_{t-j}$, substitution of the tentative solution for $\underline{y}_t$ and of the generating process for the exogenous variables into equation (26) provides the set of restrictions:

$$\Gamma_j = A\Gamma_{j+1} + D\Theta_j \ . \tag{35}$$

Focusing on the case $j = 0$, that is on the matrix equation $\Gamma_0 = A\Gamma_1 + D\Theta_0$, it is easy to see that it includes $2n^2$ unknowns, namely the elements Γ_0 and Γ_1, and only n^2 restrictions, so that n^2 additional conditions are needed. nk of them are provided by the zeros in the lower block of the matrix Γ_0, which corresponds to the set of predetermined variables. Considering the homogeneous counterpart of (35) in the case of $j = 1$, the stability requirement for the solution implies that $\Gamma_{11} = -H_{11}^{-1} H_{12} \Gamma_{20}$, as shown in (33). These constraints provide the missing $n(n-k)$ restrictions which allow the remaining elements of the matrices Γ_0 and Γ_1 to be determined. Solving (34) iteratively for $j = 1$ allows one to recover the whole sequence $\left\{ \Gamma_j^H \right\}_{j=1}^{\infty}$. In the simplified case in which $\Theta_j = \Theta^j$ a particular solution is given by $\left\{ \Gamma_j^P = \Xi\Theta^j \right\}_{j=0}^{\infty}$.

6. An empirical illustration

In this section we provide an example of the approach outlined above using the model presented in Ireland (2000); the model includes two distinct monetary policy transmission channels: (i) a traditional direct effect of the real interest rate on output (hereafter, IS channel); (ii) an indirect effect that transits through real money balances (hereafter, RB channel). Money holdings enter both the IS equation and the Phillips curve because households' utility function is assumed non-separable across consumption and real balances: this feature gives additional leverage to monetary policy actions, which can manipulate liquidity holdings by changing the opportunity cost of idle money.

For our purposes, a detailed discussion of Ireland's (2000) model is not necessary. Suffice it to say that the equilibrium values of output and inflation are obtained by solving the system composed of the IS and Phillips curve, while real money balances are post-recursively determined through a money demand equation. Monetary policy is modelled as a Taylor-type rule, augmented with nominal money growth. The model is driven by four exogenous processes: total factor productivity, a disturbance to the monetary policy rule and two preference shocks, which translate, in equilibrium, into disturbances to the IS and money demand curves. The linearized first order conditions result in the following set of eight equations in eight endogenous variables:

$$\begin{aligned}
(36) \qquad y_t &= E_t y_{t+1} - \omega_1(r_t - E_t\pi_{t+1}) \\
&\quad + \omega_2[(m_t - e_t) - (E_t m_{t+1} - E_t e_{t+1})] + \omega_1(a_t - E_t a_{t+1}) \\
(37) \qquad m_t &= \gamma_1 y_t - \gamma_2 r_t + \gamma_3 e_t \\
(38) \qquad \pi_t &= (\pi/r)E_t\pi_{t+1} + \psi[(1/\omega_1)y_t - (\omega_2/\omega_1)(m_t - e_t) - z_t] \\
(39) \qquad r_t &= \rho_y y_t + \rho_\pi \pi_t + \rho_\mu \mu_t + \varepsilon_{rt} \\
(40) \qquad \mu_t &= m_t - m_{t-1} + \pi_t \\
(41) \qquad a_t &= \rho_a a_{t-1} + \varepsilon_{at} \\
(42) \qquad e_t &= \rho_e e_{t-1} + \varepsilon_{et} \\
(43) \qquad z_t &= \rho_z z_{t-1} + \varepsilon_{zt}
\end{aligned}$$

All variables are expressed as deviations from their steady-state values; a_t and e_t are preference shocks, z_t represents productivity, y_t is output, m_t is real money balances, π_t is the inflation rate, r_t is the policy interest rate and μ_t is money growth. The model is estimated by maximum likelihood using US data from 1980.Q1 to 1999.Q2 and matches satisfactorily the vector autocorrelation function of the data.

The unconstrained estimate of the elasticity of the output gap and inflation to real balances turns out to be negligible. ω_2 is actually negative, although not statistically significant: neither a Wald nor a likelihood ratio test rejects the null hypothesis that real balances fail to enter the IS and Phillips curves. Ireland interprets this outcome as supporting the minimal treatment of money in the new vintage of micro-funded monetary models of the type popularized by Rotemberg and Woodford (1997). Ireland also presents a set of constrained estimates, in which ω_2 is restricted to be positive, but the fit of the model deteriorates significantly and the overall properties of the system do not change significantly, which reinforces the claim that money's role in the monetary business cycle is limited.[12] Our decomposition of the overall effects of monetary policy suggests that that conclusion is not entirely warranted, although for reasons that might be unexpected *a priori*.

To apply the approach proposed in this paper to the model in Ireland (2000) we need to modify the original model as follow:

$$\begin{aligned} y_t &= E_t y_{t+1} - \omega_1 (r_t^{IS} - E_t \pi_{t+1}) \\ &+ \omega_2 [(m_t - e_t) - (E_t m_{t+1} - E_t e_{t+1})] + \omega_1 (a_t - E_t a_{t+1}) \end{aligned} \tag{44}$$

$$m_t = \gamma_1 y_t - \gamma_2 r_t^{RB} + \gamma_3 e_t \tag{45}$$

$$\pi_t = (\pi/r) E_t \pi_{t+1} + \psi[(1/\omega_1) y_t - (\omega_2/\omega_1)(m_t - e_t) - z_t] \tag{46}$$

$$r_t^{IS} = \rho_y y_t + \rho_\pi \pi_t + \rho_\mu \mu_t + f_1 \varepsilon_{rt} \tag{47}$$

$$r_t^{RB} = \rho_y y_t + \rho_\pi \pi_t + \rho_\mu \mu_t + f_2 \varepsilon_{rt} \tag{48}$$

$$\mu_t = m_t - m_{t-1} + \pi_t \tag{49}$$

$$a_t = \rho_a a_{t-1} + \varepsilon_{at} \tag{50}$$

$$e_t = \rho_e e_{t-1} + \varepsilon_{et} \tag{51}$$

$$z_t = \rho_z z_{t-1} + \varepsilon_{zt} \tag{52}$$

Clearly, if f_1 and f_2 are both 1, one recovers the same overall effects as with the original model. With $f_1 = 1$ and $f_2 = 0$ one recovers the effects (both direct and indirect) that transit through the impact of the policy rate on the IS curve (IS channel); finally, with $f_1 = 0$ and $f_2 = 1$ one recovers the effects (both direct and indirect) that transit through the impact of the policy rate on the money demand equation (RB channel).

The experimental design is as follows: we give a unit shock to the discretionary component of the policy interest rate for one period, setting both flags equal to 1, so as to recover the overall effect. To solve the model we use the rational expectation algorithm proposed by Binder and Pesaran (1996). The overall responses of inflation, output and real

[12] The constrained and unconstrained estimated values of all the parameters in the model are shown in Table 1.

money balances for the constrained model are reported in Figures 1-3 (solid lines). Figures 4-5 show the reaction of the policy variable (r_t^{RB} and r_t^{IS}; the overall reaction is obviously identical for both variables).

Next, we alternatively set the two flags in the augmented model to either 0 or 1. Setting the first flag equal to 1 and the second equal to 0, one estimates the effects that transit through the IS channel. With the opposite flag setting one recovers the effects that transit through the real money balances channel. The two effects are shown in Figures 1-5 (specifically, the dashed line is the response that transits through the IS channel, while the dotted line is the response through the RB channel). They can be seen to sum up exactly to the overall effect for all variables.

In the simulation aimed at isolating the effects that transit through the RB channel (dotted line), one of the most prominent features is the sharp fall in real money balances. This fall largely offsets the initial shock to the policy interest rate (see, for example, the response of the interest rate through the RB channel in Figure 4) and mitigates the negative response of output to the policy tightening.

The decomposition exercise highlights a number of interesting and to some extent unexpected features of the model. First, the RB channel is quantitatively much more relevant than the IS channel in determining the overall response of the economy to the shock, which would lead one to conclude that the role of money is far from limited. Second, the RB channel is the main source of persistence in the model; by contrast, the effects that are transmitted by the IS channel tend to die out very quickly. Indeed, if one takes a closer look at the model in the light of the remark above, one does not fail to realize that the only source of dynamics in the model is the response of the policy rate to nominal money growth.

Figures 6-10 report the results obtained with the unconstrained version of Ireland's (2000) model. The results show that real money balances do still matter, even if the coefficient ω_2 is small, insignificant and actually has the wrong sign. The reason why the model is still very reactive to monetary policy is that the monetary policy rule is highly sensitive to money growth. Actually, the main reason why the overall response is smaller than the one associated with the constrained model has scarcely anything to do with the ω_2 parameter; rather, it reflects the fact that the estimate of the ω_1 parameter – i.e., the parameter that identifies the traditional IS effect – is now much smaller than before.

The experiment documented in this section is only meant to show that the approach proposed in this paper delivers an accurate decomposition of the overall effects of monetary policy on the economy even if expectations are forward-looking and monetary policy responds to the state of the economy.

However, our results suggest that this approach may provide useful insights into the propagation mechanisms of a shock, and hence may be of help in better understanding the structure and features of a model. Specifically, in both the constrained a unconstrained versions of Ireland's (2000) model, the real money balances channel is by far the quantitatively most relevant channel in shaping the overall results, despite the fact that the sign of the direct effect of real money balances on output (through the IS curve) is exactly the opposite in the two versions of the model (being negative, i.e., of the wrong sign, in the unconstrained version). This is so because the estimated parameters imply a high sensitivity of nominal money balances to the interest rate and, most importantly, the latter responds to the rate of growth of money, given the specification of the monetary reaction function. The latter thus stands out as a key feature of the model in that it plays a very prominent role (possibly unexpected a priori) in shaping the overall results.

Table 1 - Ireland's (2000) estimated parameter values

Parameters	Unconstrained	Constrained
ω_1	0.0548	0.2554
ω_2	-0.0199	0.1500
γ_1	1.4337	2.062
γ_2	7.7532	6.3712
γ_3	0.8553	0.8823
ρ_y	0.0288	0.0668
ρ_π	0.7589	0.7766
ρ_μ	0.8126	0.8743
ρ_a	0.9426	0.9462
ρ_e	0.9482	0.9439
ρ_z	0.9308	0.9013
σ_a	0.1518	0.0474
σ_e	0.0188	0.0171
σ_z	0.7199	0.2214
σ_r	0.0062	0.0066

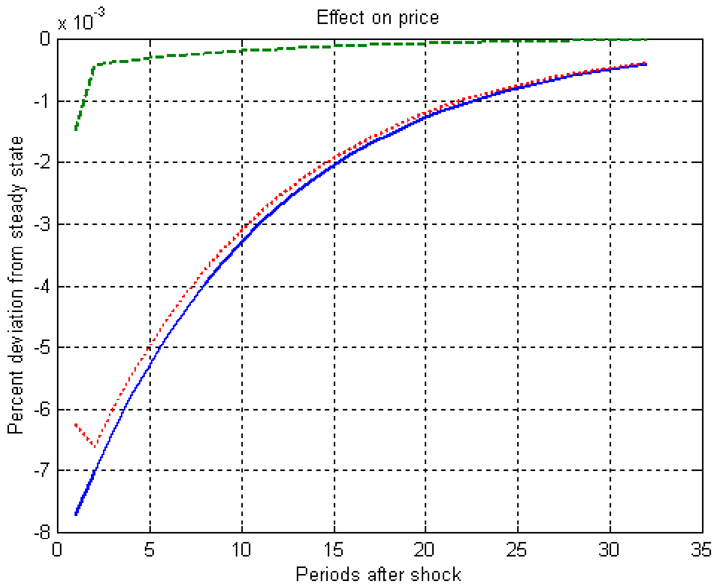

Figure 1 - Unconstr. - Solid: total effect; dashed: IS ch.; dotted: RB ch..

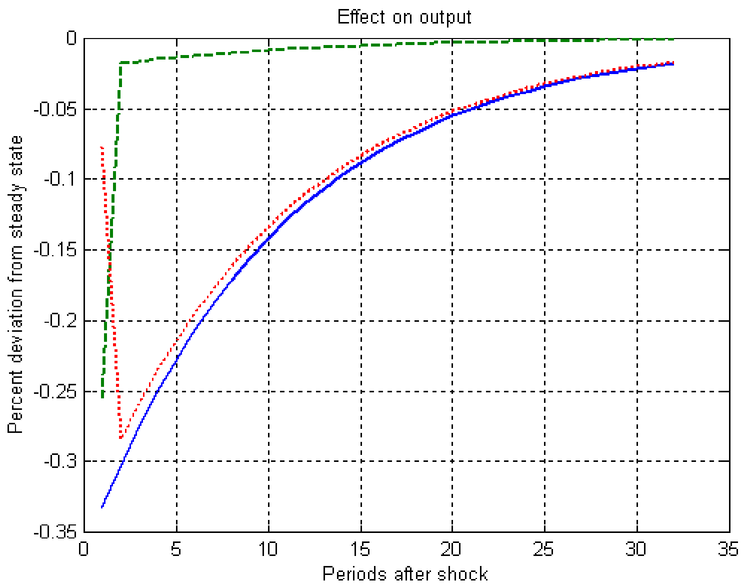

Figure 2 - Unconstr. - Solid: total effect; dashed: IS ch.; dotted: RB ch..

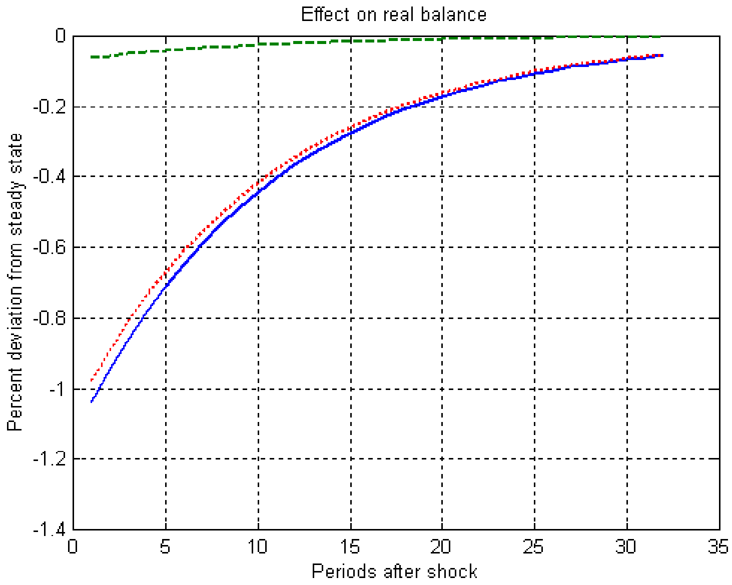

Figure 3 - Unconstr. - Solid: total effect; dashed: IS ch.; dotted: RB ch..

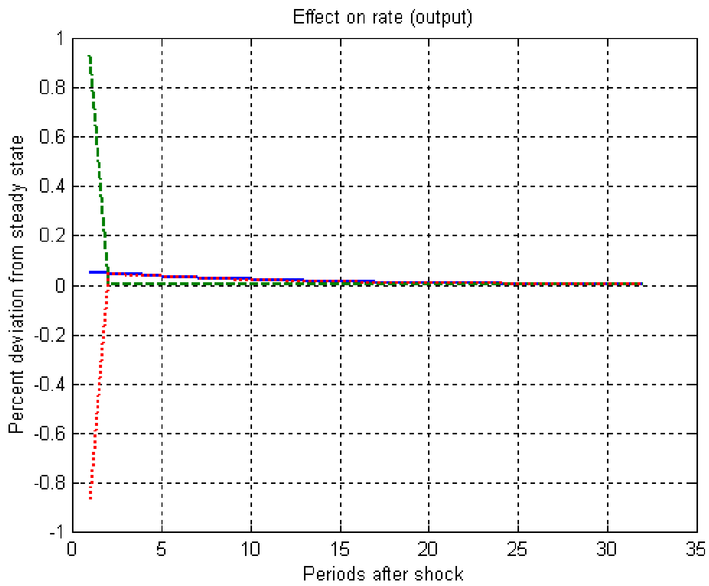

Figure 4 - Unconstr. - Solid: total effect; dashed: IS ch.; dotted: RB ch..

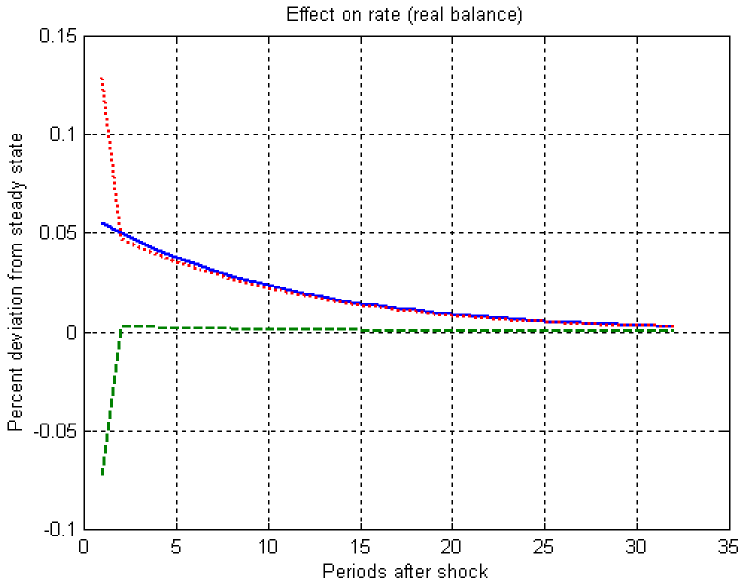

Figure 5 - Unconstr. - Solid: total effect; dashed: IS ch.; dotted: RB ch..

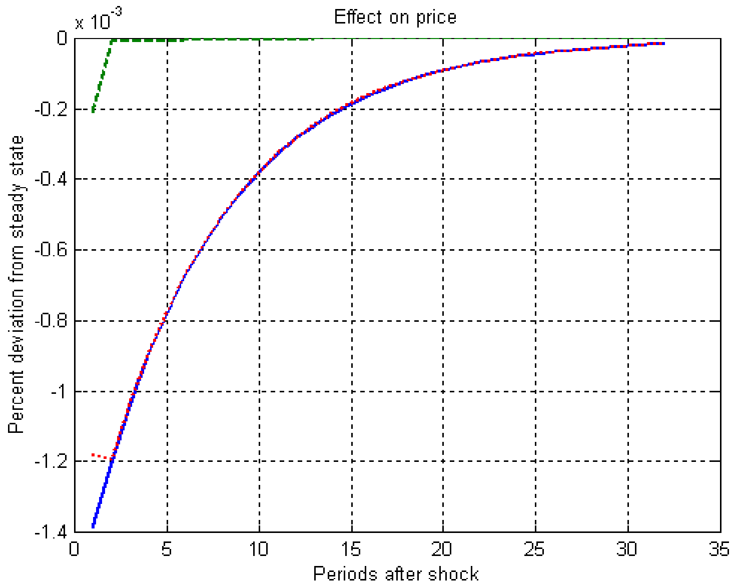

Figure 6 - Constr. - Solid: total effect; dashed: IS ch.; dotted: RB ch..

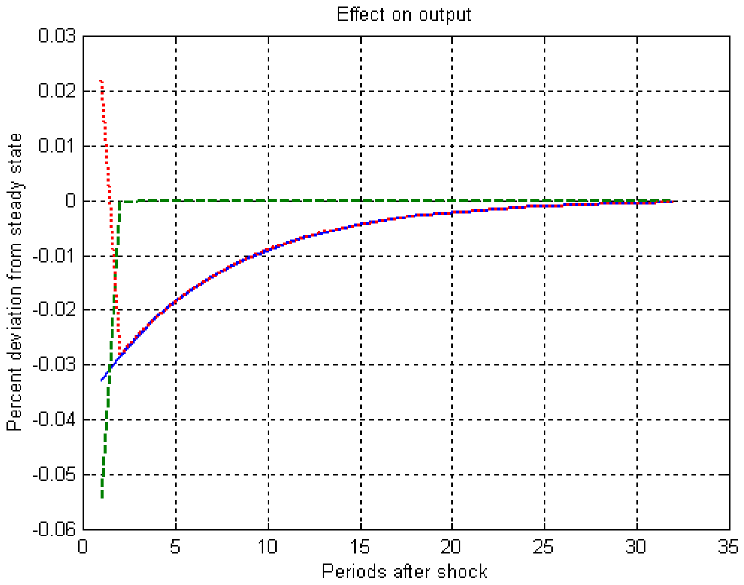

Figure 7 - Constr. - Solid: total effect; dashed: IS ch.; dotted: RB ch..

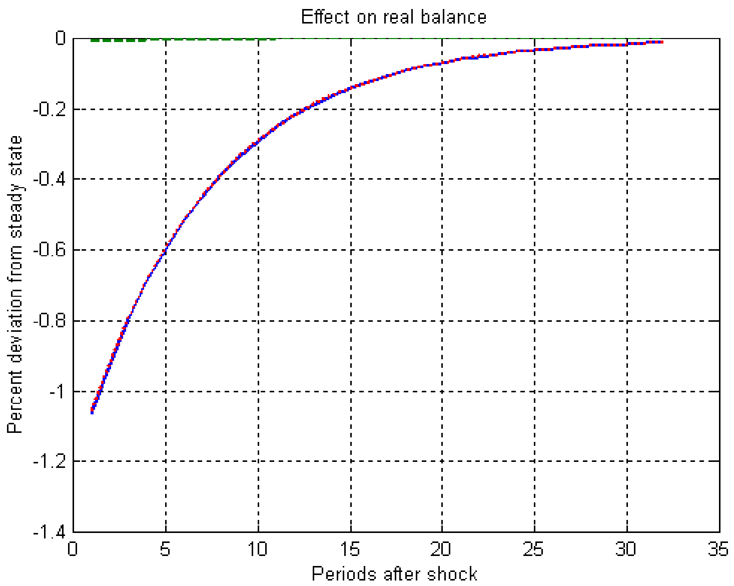

Figure 8 - Constr. - Solid: total effect; dashed: IS ch.; dotted: RB ch..

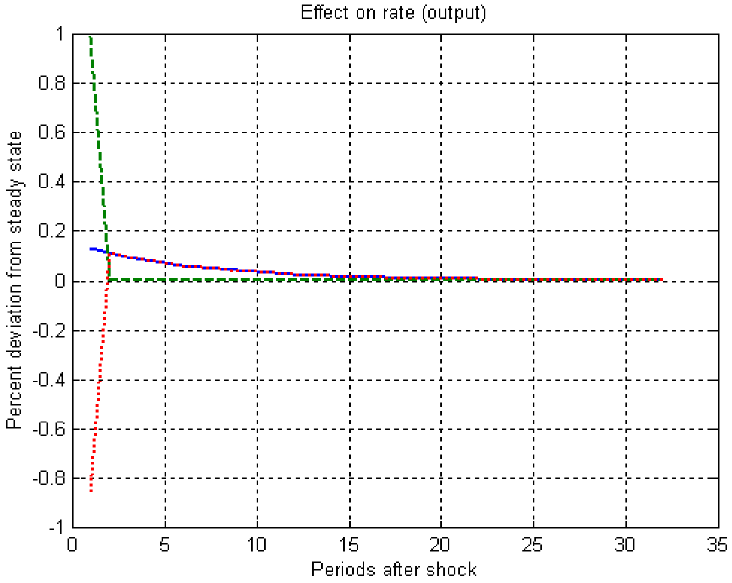

Figure 9 - Constr. - Solid: total effect; dashed: IS ch.; dotted: RB ch..

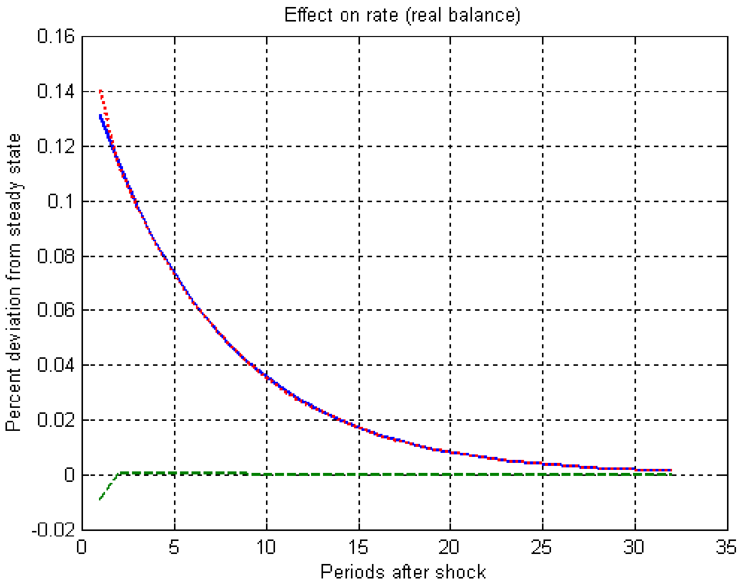

Figure 10 - Constr. - Solid: total effect; dashed: IS ch.; dotted: RB ch..

7. Non linearity

As soon as one leaves the linear world, the clear-cut conclusions reached in the previous sections all tend to collapse, as in fact one would expect *a priori*: specifically, for any given shock to the policy variable it will in general no longer be true that the sum of the partial channel-specific reactions of the endogenous variables to the shock matches the total reaction.

The accuracy of the decomposition will tend to deteriorate as the size of the shock increases; for an infinitely small shock the decomposition will still be accurate. Moreover, if the model is non linear it does matter how the effects of a shock are computed. By contrast, in the linear case the results are unaffected by the sequence in which they are evaluated.

Although non linearity seems at first to be an unpromising case, a few qualifications can still be made.

First, it is usually the case that the degree of non linearity of most macroeconometric models is very limited (as measured, for example, by the size of the deterministic bias; see the extensive results reported in Fisher and Salmon (1986)). Second, for a small enough shock an accurate decomposition is still possible, as mentioned. Third, one may somehow check for the effects of nonlinearity deriving a measure of its relevance. One way this may be done is by changing the sequence in which the effects of the various channels are measured. For instance, the effects that transit through each channel may be evaluated in two different ways, namely by adopting either a bottom-up or a top-down approach. In the first case, the size of the channel is computed by means of a single simulation in which the flag identifying the channel is set equal to 1 while all the others are set to 0; in the second case, it is computed indirectly as the difference between the overall effect and the one attributable to the other channel. This way of proceeding will result in an interval, rather than a point value, for the effects associated with each channel. The width of the interval may be viewed as providing a measure of the degree of non linearity of the model, as an alternative to the standard deterministic bias.

To illustrate these remarks let us consider again the model used in the previous section. The model was modified by arbitrarily introducing an exponential function for the impact of the policy rate on money balances (the exponential function was calibrated to give the same baseline solution as the original model). The overall effect on inflation of a shock to the discretionary component of monetary policy is shown in Figure 11, together with the effects associated with each of the two channels IS and RB. Only the impact multiplier is shown in the figure, for shock sizes between -100 and 100 basis points.

The overall multiplier is almost constant across the shock range depicted in the figure. The same does not hold for the effects associated with each individual channel. Computing these effects both directly and indirectly results in a range that tends to become larger as the (absolute) size of the shock increases. However, it may be seen that in this particular case the two ranges are far from overlapping.

8. Conclusions

We have shown that an appropriately designed system of “flags” may be used to separately assess the empirical relevance of the various monetary policy transmission channels at play in an (estimated or calibrated) model. The approach is an extension of the one originally proposed in Mauskopf-Siviero (1994). We have shown that, contrary to the fears expressed by a number of authors, that approach is not only well suited to deal with the vanilla case of a backward-looking model but may also handle, with slight modifications, the case in which expectations are forward-looking and/or a policy reaction function is postulated.

Only non linearity puts a strain on the accuracy of the approach. However, such a result is largely expected. Moreover, the degree of non linearity of most models of the macroeconomy is by and large rather limited. Also, ways to control for the effects of non linearity may be designed.

The exercise presented in the paper suggests that this approach may provide useful (and, in the specific case considered here, somewhat unexpected) insight into the features of an empirical model.

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