

# Existence, uniqueness and computation of solutions to DSGE models with occasionally binding constraints.

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**Abstract:** *In this paper we present the first necessary and sufficient conditions for the existence of a unique perfect-foresight solution to an otherwise linear model with occasionally binding constraints, such as the zero lower bound on nominal interest rates. We also derive both necessary conditions and sufficient conditions for the existence of a solution to such a model. We go on to construct the first solution algorithm for these problems that is guaranteed to return a solution in finite time, if one exists. Moreover, in the presence of multiple solutions, the solution algorithm is able to always select the one that maximises an intuitive criterion. This solution algorithm is first extended to non-linear models, and then further extended to take into account future uncertainty, both in the short run, and in the longer run via a novel hybrid of local and global approaches. Our solution algorithm is shown to produce accurate simulations on a wide range of DSGE models with occasionally binding constraints.*

**Keywords:** *occasionally binding constraints, zero lower bound, DSGE, linear complementarity problem, LCP*

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## 1. Introduction

TODO

## 2. Occasionally binding constraints in otherwise linear models under perfect foresight

### 2.1. Theoretical results

#### 2.1.1. Problem set-ups

Suppose that for  $t \in \mathbb{N}^+$ , (i.e.  $t \in \mathbb{N}, t > 0$ ):

$$(\hat{A} + \hat{B} + \hat{C})\hat{\mu} = \hat{A}\hat{x}_{t-1} + \hat{B}\hat{x}_t + \hat{C}\mathbb{E}_t\hat{x}_{t+1} + \hat{D}\varepsilon_t,$$

where  $\mathbb{E}_{t-1}\varepsilon_t = 0$  for all  $t \in \mathbb{N}^+$ , and suppose that  $\hat{x}_0$  is given as an initial condition. Furthermore, suppose that  $\varepsilon_t = 0$  for  $t > 1$ , as in an impulse response or perfect foresight simulation exercise. Additionally, we assume the existence of a the terminal condition of the form  $\hat{x}_t \rightarrow \hat{\mu}$  as  $t \rightarrow \infty$ , coming, for example, from the model's transversality constraints.

For  $t \in \mathbb{N}^+$ , define:

$$x_t := \begin{bmatrix} \hat{x}_t \\ \varepsilon_{t+1} \end{bmatrix}, \quad \mu := \begin{bmatrix} \hat{\mu} \\ 0 \end{bmatrix}, \quad A := \begin{bmatrix} \hat{A} & \hat{D} \\ 0 & 0 \end{bmatrix}, \quad B := \begin{bmatrix} \hat{B} & 0 \\ 0 & I \end{bmatrix}, \quad C := \begin{bmatrix} \hat{C} & 0 \\ 0 & 0 \end{bmatrix}$$

then, for  $t \in \mathbb{N}^+$ :

$$(A + B + C)\mu = Ax_{t-1} + Bx_t + Cx_{t+1},$$

and we have the extended initial condition  $x_0 = \begin{bmatrix} \hat{x}_0 \\ \varepsilon_1 \end{bmatrix}$ , and the extended terminal condition  $x_t \rightarrow \mu$  as  $t \rightarrow \infty$ .

Expectations have disappeared since there is no uncertainty after period 0. Thus, the problem of solving the original model has the form as that given in:

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#### **Problem 1**

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Suppose that  $x_0 \in \mathbb{R}^n$  is given. Find  $x_t \in \mathbb{R}^n$  for  $t \in \mathbb{N}^+$  such that  $x_t \rightarrow \mu$  as  $t \rightarrow \infty$ , and such that for all  $t \in \mathbb{N}^+$ :

$$(A + B + C)\mu = Ax_{t-1} + Bx_t + Cx_{t+1}.$$


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We make the following assumption in all of the following:

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#### **Assumption 1**

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For any given  $x_0 \in \mathbb{R}^n$ , Problem 1 has a unique solution, which takes the form  $x_t = (I - F)\mu + Fx_{t-1}$ , for  $t \in \mathbb{N}^+$ , where  $F = -(B + CF)^{-1}A$ .

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Sims's (2002) generalisation of the standard Blanchard-Kahn (1980) conditions is necessary and sufficient for this.

We are interested in models featuring occasionally binding constraints. For now, we will concentrate on models featuring a single zero lower bound type constraint in their first equation, which we treat as defining the first element of  $x_t$ . Generalising from this special case will be straightforward. First, let us define  $I$  as the  $T \times T$  identity matrix, and let us write  $x_{1,t}$ ,  $I_{1,\cdot}$ ,  $A_{1,\cdot}$ ,  $B_{1,\cdot}$ ,  $C_{1,\cdot}$  for the first row of  $x_t$ ,  $I$ ,  $A$ ,  $B$ ,  $C$  (respectively) and

$x_{-1,t}, I_{-1,t}, A_{-1,t}, B_{-1,t}, C_{-1,t}$ , for the remainders. (Similar notation will be adopted for the rest of this paper.) Then we are interested in the solution to:

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**Problem 2**


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Suppose that  $x_0 \in \mathbb{R}^n$  is given. Find  $T \in \mathbb{N}$  and  $x_t \in \mathbb{R}^n$  for  $t \in \mathbb{N}^+$  such that  $x_t \rightarrow \mu$  as  $t \rightarrow \infty$ , and such that for all  $t \in \mathbb{N}^+$ :

$$x_{1,t} = \max\{0, I_{1,t}\mu + A_{1,t}(x_{t-1} - \mu) + (B_{1,t} + I_{1,t})(x_t - \mu) + C_{1,t}(x_{t+1} - \mu)\},$$

$$(A_{-1,t} + B_{-1,t} + C_{-1,t})\mu = A_{-1,t}x_{t-1} + B_{-1,t}x_t + C_{-1,t}x_{t+1},$$

and such that  $x_{1,t} > 0$  for  $t > T$ .

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Note that in this problem we are implicitly ruling out any solutions which get permanently stuck at an alternative steady-state, by assuming that the terminal condition remains as before. Indeed, we are assuming that the bound is only relevant for some finite number of periods  $T$ . We continue to assume that there is no uncertainty after period 0, so, in this non-linear model, the path of the endogenous variables will not necessarily match up with the path of their expectation in a richer model in which there was uncertainty after period 0.

We will analyse this problem with the help of solutions to the following auxiliary problem:

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**Problem 3**


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Suppose that  $T \in \mathbb{N}$ ,  $x_0 \in \mathbb{R}^n$  and  $y_0 \in \mathbb{R}^T$  is given. Find  $x_t \in \mathbb{R}^n, y_t \in \mathbb{R}^T$  for  $t \in \mathbb{N}^+$  such that  $x_t \rightarrow \mu$ ,  $y_t \rightarrow 0$ , as  $t \rightarrow \infty$ , and such that for all  $t \in \mathbb{N}^+$ :

$$(A + B + C)\mu = Ax_{t-1} + Bx_t + Cx_{t+1} + I_{1,t}I_{1,t}y_{t-1},$$

$$\forall i \in \{1, \dots, T-1\}, \quad y_{i,t} = y_{i+1,t-1},$$

$$y_{T,t} = 0.$$


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This may be thought of as a version of Problem 1 with news shocks up to horizon  $T$  added to the first equation.<sup>2</sup> The value of  $y_{t,0}$  gives the news shock that hits in period  $t$ , i.e.  $I_{1,t}y_{t-1} = y_{1,t-1} = y_{t,0}$  for  $t \leq T$ , and  $I_{1,t}y_{t-1} = y_{1,t-1} = 0$  for  $t > T$ .

**2.1.2. Relationships between the problems**

Together with Assumption 1, the fact that  $I_{1,t}y_{t-1} = 0$  for  $t > T$  implies that  $(x_{T+1} - \mu) = F(x_T - \mu)$ , so with  $t = T$ , defining  $s_{T+1} := 0$ ,  $(x_{t+1} - \mu) = s_{t+1} + F(x_t - \mu)$ . Proceeding now by backwards induction on  $t$ , note that:

$$0 = A(x_{t-1} - \mu) + B(x_t - \mu) + CF(x_t - \mu) + Cs_{t+1} + I_{1,t}y_{t,0},$$

so:

$$(x_t - \mu) = -(B + CF)^{-1}[A(x_{t-1} - \mu) + Cs_{t+1} + I_{1,t}y_{t,0}] = F(x_{t-1} - \mu) - (B + CF)^{-1}(Cs_{t+1} + I_{1,t}y_{t,0}),$$

i.e., if we define:  $s_t := -(B + CF)^{-1}(Cs_{t+1} + I_{1,t}y_{t,0})$ , then  $(x_t - \mu) = s_t + F(x_{t-1} - \mu)$ . By induction then, this holds for all  $t \in \{1, \dots, T\}$ .<sup>3</sup> Hence, we have proved the following lemma:

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**Lemma 1**


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There is a unique solution to Problem 3 which is linear in  $x_0$  and  $y_0$ .

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<sup>2</sup> The idea of imposing the zero lower bound by adding news shocks is also present in Holden (2010), Hebden et al. (2011), Holden & Paetz (2012) and Bodenstein et al. (2013).

<sup>3</sup> This representation of the solution to Problem 3 was inspired by that of Anderson (2015).

For future reference, let  $x_t^{(3,k)}$  be the solution to Problem 3 when  $x_0 = \mu, y_0 = I_{\cdot,k}$  (i.e. a vector which is all zeros apart from a 1 in position  $k$ ). Then, by linearity, for arbitrary  $y_0$  the solution to Problem 3 when  $x_0 = \mu$  is given by:

$$x_t - \mu = \sum_{k=1}^T y_{k,0} (x_t^{(3,k)} - \mu).$$

Let  $M \in \mathbb{R}^{T \times T}$  satisfy:

$$M_{t,k} = x_{1,t}^{(3,k)} - \mu, \quad \forall t, k \in \{1, \dots, T\}, \quad (1)$$

i.e.  $M$  horizontally stacks the (column-vector) relative impulse responses to the news shocks. Then this result implies that for arbitrary  $y_0$ , the path of the first variable in the solution to Problem 3 when  $x_0 = \mu$  is given by:  $(x_{1,1\dots T})' = \mu_1 + My_0$ , where  $x_{1,1\dots T}$  is the row vector of the first  $T$  values of the first component of  $x_t$ . Furthermore, for both arbitrary  $x_0$  and  $y_0$ , the path of the first variable in the solution to Problem 3 is given by:  $(x_{1,1\dots T})' = q + My_0$ , where  $q := (x_{1,1\dots T}^{(1)})'$  and  $x_t^{(1)}$  is the unique solution to Problem 1, for the given  $x_0$ .<sup>4</sup> This ease in solving Problem 3 given  $y_0$  will be crucial to the efficiency of our eventual solution algorithm for Problem 2.

Now let  $x_t^{(2)}$  be a solution to Problem 2 given an arbitrary  $x_0$ . Since  $x_t^{(2)} \rightarrow \mu$  as  $t \rightarrow \infty$ , there exists  $T' \in \mathbb{N}$  such that for all  $t > T'$ ,  $x_{1,t}^{(2)} > 0$ . We assume without loss of generality that  $T' \leq T$ . We seek to relate the solution to Problem 2 with the solution to Problem 3 for an appropriate choice of  $y_0$ .

First, for all  $t \in \mathbb{N}^+$ , let:

$$e_t := \begin{cases} -[I_{1,\cdot}\mu + A_{1,\cdot}(x_{t-1}^{(2)} - \mu) + (B_{1,\cdot} + I_{1,\cdot})(x_t^{(2)} - \mu) + C_{1,\cdot}(x_{t+1}^{(2)} - \mu)] & \text{if } x_{1,t}^{(2)} = 0 \\ 0 & \text{if } x_{1,t}^{(2)} > 0 \end{cases} \quad (2)$$

i.e.  $e_t$  is the shock that would need to hit the first equation for the positivity constraint on  $x_{1,t}^{(2)}$  to be enforced. Note for future reference that by the definition of Problem 2,  $e_t \geq 0$  and  $x_{1,t}^{(2)}e_t = 0$ , for all  $t \in \mathbb{N}^+$ . From this definition, we also have that for all  $t \in \mathbb{N}^+$ :

$$0 = A(x_{t-1}^{(2)} - \mu) + B(x_t^{(2)} - \mu) + C(x_{t+1}^{(2)} - \mu) + I_{\cdot,1}e_t.$$

Furthermore, if  $t > T$ , then  $t > T'$ , and hence  $e_t = 0$ . Hence, by Assumption 1,  $(x_{T+1}^{(2)} - \mu) = F(x_T^{(2)} - \mu)$ . Thus, much as before, with  $t = T$ , defining  $r_{T+1} := 0$ ,  $(x_{t+1}^{(2)} - \mu) = r_{t+1} + F(x_t^{(2)} - \mu)$ . Consequently:

$$0 = A(x_{t-1}^{(2)} - \mu) + B(x_t^{(2)} - \mu) + CF(x_t^{(2)} - \mu) + Cr_{t+1} + I_{\cdot,1}e_t,$$

so:

$$(x_t^{(2)} - \mu) = F(x_{t-1}^{(2)} - \mu) - (B + CF)^{-1}(Cr_{t+1} + I_{\cdot,1}e_t),$$

i.e., if we define:  $r_t := -(B + CF)^{-1}(Cr_{t+1} + I_{\cdot,1}e_t)$ , then  $(x_t^{(2)} - \mu) = r_t + F(x_{t-1}^{(2)} - \mu)$ . As before, by induction this must hold for all  $t \in \{1, \dots, T\}$ . By comparing the definitions of  $s_t$  and  $r_t$ , and the laws of motion of  $x_t$  under both problems, we then immediately have that if Problem 3 is started with  $x_0 = x_0^{(2)}$  and  $y_0 = e'_{1\dots T}$ , then  $x_t^{(2)}$  solves Problem 3. Conversely, if  $x_t^{(2)}$  solves Problem 3 for some  $y_0$ , then from the laws of motion of  $x_t$  under both problems it must be the case that  $r_t = s_t$  for all  $t \in \mathbb{N}$ , and hence from the definitions of  $s_t$  and  $r_t$ , we have that  $y_0 = e'_{1\dots T}$ . This has established the following result:

<sup>4</sup> This representation was also exploited by Holden (2010) and Holden & Paetz (2012).

**Lemma 2**

For any solution,  $x_t^{(2)}$  to Problem 2:

- 1) With  $e_{1...T}$  as defined in equation (2),  $e_{1...T} \geq 0$ ,  $x_{1,1...T}^{(2)} \geq 0$  and  $x_{1,1...T}^{(2)} \circ e_{1...T} = 0$ , where  $\circ$  denotes the Hadamard (entry-wise) product.
- 2)  $x_t^{(2)}$  is also the unique solution to Problem 3 when started with  $x_0 = x_0^{(2)}$  and with  $y_0 = e'_{1...T}$ .
- 3) If  $x_t^{(2)}$  solves Problem 3 when started with  $x_0 = x_0^{(2)}$  and with some  $y_0$ , then  $y_0 = e'_{1...T}$ .

However, to use the easy solution to Problem 3 to assist us in solving Problem 2 requires a slightly stronger result. Suppose that  $y_0 \in \mathbb{R}^T$  is such that  $y_0 \geq 0$ ,  $x_{1,1...T}^{(3)} \circ y'_0 = 0$  and  $x_{1,t}^{(3)} \geq 0$  for all  $t \in \mathbb{N}$ , where  $x_t^{(3)}$  is the unique solution to Problem when started at  $x_0, y_0$ . We would like to prove that in this case  $x_t^{(3)}$  must also be a solution to Problem 2. I.e., we must prove that for all  $t \in \mathbb{N}^+$ :

$$x_{1,t}^{(3)} = \max\{0, I_{1,\cdot}\mu + A_{1,\cdot}(x_{t-1}^{(3)} - \mu) + (B_{1,\cdot} + I_{1,\cdot})(x_t^{(3)} - \mu) + C_{1,\cdot}(x_{t+1}^{(3)} - \mu)\},$$

$$(A_{-1,\cdot} + B_{-1,\cdot} + C_{-1,\cdot})\mu \neq A_{-1,\cdot}x_{t-1}^{(3)} + B_{-1,\cdot}x_t^{(3)} + C_{-1,\cdot}x_{t+1}^{(3)}.$$

By the definition of Problem 3, the latter equation must hold with equality, so there is nothing to prove there.

Hence we just need to prove that for all  $t \in \mathbb{N}^+$ :

$$x_{1,t}^{(3)} = \max\{0, I_{1,\cdot}\mu + A_{1,\cdot}(x_{t-1}^{(3)} - \mu) + (B_{1,\cdot} + I_{1,\cdot})(x_t^{(3)} - \mu) + C_{1,\cdot}(x_{t+1}^{(3)} - \mu)\}.$$

Let  $t \in \mathbb{N}^+$ . Now, if  $x_{1,t}^{(3)} > 0$ , then  $y_{t,0} = 0$ , by the complementary slackness type condition ( $x_{1,1...T}^{(3)} \circ y'_0 = 0$ ).

Thus, from the definition of Problem 3:

$$(A + B + C)\mu = Ax_{t-1} + Bx_t + Cx_{t+1},$$

so:

$$x_{1,t}^{(3)} = I_{1,\cdot}\mu + A_{1,\cdot}(x_{t-1}^{(3)} - \mu) + (B_{1,\cdot} + I_{1,\cdot})(x_t^{(3)} - \mu) + C_{1,\cdot}(x_{t+1}^{(3)} - \mu)$$

$$= \max\{0, I_{1,\cdot}\mu + A_{1,\cdot}(x_{t-1}^{(3)} - \mu) + (B_{1,\cdot} + I_{1,\cdot})(x_t^{(3)} - \mu) + C_{1,\cdot}(x_{t+1}^{(3)} - \mu)\},$$

as required. The only remaining case is that  $x_{1,t}^{(3)} = 0$  (since  $x_{1,t}^{(3)} \geq 0$  for all  $t \in \mathbb{N}$ , by assumption), which implies that:

$$x_{1,t}^{(3)} = 0 = A_{1,\cdot}(x_{t-1} - \mu) + B_{1,\cdot}(x_t - \mu) + C_{1,\cdot}(x_{t+1} - \mu) + y_{t,0}$$

$$= I_{1,\cdot}\mu + A_{1,\cdot}(x_{t-1} - \mu) + (B_{1,\cdot} + I_{1,\cdot})(x_t - \mu) + C_{1,\cdot}(x_{t+1} - \mu) + y_{t,0},$$

by the definition of Problem 3. Thus:

$$I_{1,\cdot}\mu + A_{1,\cdot}(x_{t-1} - \mu) + (B_{1,\cdot} + I_{1,\cdot})(x_t - \mu) + C_{1,\cdot}(x_{t+1} - \mu) = -y_{t,0} \leq 0,$$

where the inequality is an immediate consequence of another of our assumptions. Consequently:

$$x_{1,t}^{(3)} = \max\{0, I_{1,\cdot}\mu + A_{1,\cdot}(x_{t-1}^{(3)} - \mu) + (B_{1,\cdot} + I_{1,\cdot})(x_t^{(3)} - \mu) + C_{1,\cdot}(x_{t+1}^{(3)} - \mu)\},$$

as required. Together with Lemma 1, Lemma 2, and our representation of the solution of Problem 3, this completes the proof of the following proposition:

**Proposition 1**

- 1) Let  $x_t^{(3)}$  be the unique solution to Problem 3 when initialized with some  $x_0, y_0$ . Then  $x_t^{(3)}$  is a solution to Problem 2 when initialized with  $x_0$  if and only if  $y_0 \geq 0$ ,  $y_0 \circ (q + My_0) = 0$ ,  $q + My_0 \geq 0$  and  $x_{1,t}^{(3)} \geq 0$  for all  $t \in \mathbb{N}$  with  $t > T$ .
- 2) Let  $x_t^{(2)}$  be any solution to Problem 2 when initialized with  $x_0$ . Then there exists a  $y_0 \in \mathbb{R}^T$  such that  $y_0 \geq 0$ ,  $y_0 \circ (q + My_0) = 0$ ,  $q + My_0 \geq 0$ , such that  $x_t^{(2)}$  is the unique solution to Problem 3 when initialized with  $x_0, y_0$ .

### 2.1.3. The linear complementarity representation

Proposition 1 establishes that providing we initially choose  $T$  sufficiently high, to find a solution to Problem 2, it is sufficient to solve Problem 4 then perform some trivial linear calculations.

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#### **Problem 4 (Linear Complementarity Problem (LCP))**

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Suppose  $q \in \mathbb{R}^T$  and  $M \in \mathbb{R}^{T \times T}$  are given. Find  $y \in \mathbb{R}^T$  such that  $y \geq 0$ ,  $y \circ (q + My) = 0$  and  $q + My \geq 0$ . We call this the linear complementarity problem  $(q, M)$ .

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In the mathematical and optimisation literatures, Problem 4 is called a linear complementarity problem or LCP (Cottle 2009). These problems have been extensively studied, and so we can import results on the properties of LCPs to derive results on the properties of solutions to models with occasionally binding constraints.

All of the results in the mathematical literature rest on properties of the matrix  $M$ , thus we must first establish if the structure of our particular  $M$  implies it has any special properties. Unfortunately it seems that  $M$  has no general properties. We show this by constructing a model for each matrix in  $\mathbb{R}^{T \times T}$ , such that the  $M$  matrix the model produces is precisely the matrix we started with.

Let  $M \in \mathbb{R}^{T \times T}$ . Consider a model with the following equations:

$$\begin{aligned} a_t &= \max\{0, b_t\}, \\ a_t &= 1 + \sum_{j=1}^T \sum_{k=1}^T M_{j,k} (c_{j-1,k-1,t} - c_{j,k,t}), \\ c_{0,0,t} &= a_t - b_t, \\ c_{0,k,t} &= \mathbb{E}_t c_{0,k-1,t+1}, \quad \forall k \in \{1, \dots, T\}, \\ c_{j,k,t} &= c_{j-1,k,t-1}, \quad \forall j \in \{1, \dots, T\}, k \in \{0, \dots, T\}, \end{aligned}$$

with steady-state  $a_t = b_t = 1$ ,  $c_{j,k,t} = 0$  for all  $j, k \in \{0, \dots, T\}$ . Defining:

$$x_t := [a_t \quad b_t \quad (\text{vec } c_{\cdot,\cdot,t})']'$$

and dropping expectations, this model is then in the form of Problem 2.

Now consider the model's Problem 3 type equivalent, in which for  $t \in \mathbb{N}^+$ :

$$a_t = \begin{cases} b_t + y_{t,0} & \text{if } t \leq T \\ b_t & \text{if } t > T' \end{cases}$$

where  $y_{\cdot,\cdot}$  is defined as in Problem 3.

Thus, if  $c_{j,k,0} = 0$  for all  $j, k \in \{0, \dots, T\}$ , then for all  $t \in \mathbb{N}^+$ ,  $j, k \in \{0, \dots, T\}$ :

$$\begin{aligned} c_{0,k,t} &= \begin{cases} y_{t+k,0} & \text{if } t+k \leq T \\ 0 & \text{if } t+k > T' \end{cases} \\ c_{j,k,t} &= \begin{cases} c_{0,k,t-j} & \text{if } t-j > 0 \\ 0 & \text{if } t-j \leq 0 \end{cases} = \begin{cases} y_{t+k-j,0} & \text{if } t-j > 0, t+k-j \leq T \\ 0 & \text{otherwise} \end{cases}. \end{aligned}$$

Hence, for all  $t \in \mathbb{N}^+$ ,  $j, k \in \{1, \dots, T\}$ :

$$c_{j-1,k-1,t} - c_{j,k,t} = \begin{cases} y_{t+k-j,0} & \text{if } t-j = 0, t+k-j \leq T \\ 0 & \text{otherwise} \end{cases} = \begin{cases} y_{k,0} & \text{if } t = j \\ 0 & \text{otherwise} \end{cases}.$$

Therefore, for all  $t \in \{1, \dots, T\}$ :

$$a_t - 1 = \sum_{k=1}^T M_{t,k} y_{k,0}.$$

Consequently, if  $y_{k,0} = I_{\cdot,l}$  for some  $l \in \{1, \dots, T\}$ , then  $a_t - 1 = M_{t,l}$ , i.e. the relative impulse response to a news-shock at horizon  $l$  is the  $l^{\text{th}}$  column of  $M$ . This establishes the following proposition:

**Proposition 2**

For any matrix  $M \in \mathbb{R}^{T \times T}$ , there exists a model in the form of Problem 2 with a number of state variables given by a quadratic in  $T$ , such that  $M = \bar{M}$  for that model, where  $\bar{M}$  is defined as in equation (1).

We now introduce some definitions of matrix properties that are necessary for the statement of our key existence and uniqueness results. The ultimate properties of the occasionally binding constraint model are determined by which of these matrix properties  $M$  possesses. In each case, we give the definitions in a constructive form which makes clear both how the property might be verified computationally, and the links between definitions. These are not necessarily in the form which is standard in the original literature, however. For both the original definitions, and the proofs of equivalence between the ones below and the originals, see Cottle, Pang, and Stone (2009) and Xu (1993) (for the characterisation of sufficient matrices).

**Definition 1 (Principal sub-matrix, Principal minor)**

For a matrix  $M \in \mathbb{R}^{T \times T}$ , the **principal sub-matrices** of  $M$  are the matrices:

$$\left\{ [M_{i,j}]_{i,j=k_1, \dots, k_S} \mid S, k_1, \dots, k_S \in \{1, \dots, T\}, k_1 < k_2 < \dots < k_S \right\},$$

i.e. the **principal sub-matrices** of  $M$  formed by deleting the same rows and columns.

The **principal minors** of  $M$  are the collection of values:

$$\left\{ \det \left( [M_{i,j}]_{i,j=k_1, \dots, k_S} \right) \mid S, k_1, \dots, k_S \in \{1, \dots, T\}, k_1 < k_2 < \dots < k_S \right\},$$

i.e. the **principal minors** of  $M$  are the determinants of the principal sub-matrices of  $M$ .

**Definition 2 ((Non-)Degenerate matrix)**

A matrix  $M \in \mathbb{R}^{T \times T}$  is called a **non-degenerate matrix** if the principal minors of  $M$  are all non-zero.  $M$  is called a **degenerate matrix** if it is not a non-degenerate matrix.

**Definition 3 ( $P_0$ -matrix)**

A matrix  $M \in \mathbb{R}^{T \times T}$  is called a **P-matrix** if the principal minors of  $M$  are all strictly positive.  $M$  is called a  **$P_0$ -matrix** if the principal minors of  $M$  are all non-negative. *Note: for symmetric  $M$ ,  $M$  is a P-matrix if and only if all of its eigenvalues are strictly positive, and  $M$  is a  $P_0$ -matrix if and only if all of its eigenvalues are non-negative.*

**Definition 4 (General positive (semi-)definite)**

A matrix  $M \in \mathbb{R}^{T \times T}$  is called **general positive definite** if  $M + M'$  is a P-matrix. If  $M + M'$  is a  $P_0$ -matrix, then  $M$  is called **general positive semi-definite**. *Note: that we do not require that  $M$  is symmetric in either case, but that if  $M$  is symmetric, then,  $M$  is general positive-definite if and only if it is a P-matrix and  $M$  is a general positive semi-definite if and only if it is a  $P_0$ -matrix, so in this case the definitions coincide with the standard ones.*

**Definition 5 ( $S_0$ -matrix)**

A matrix  $M \in \mathbb{R}^{T \times T}$  is called an **S-matrix** if there exists  $y \in \mathbb{R}^T$  such that  $y > 0$  and  $My \gg 0$ .  $M$  is called an  **$S_0$ -matrix** if there exists  $y \in \mathbb{R}^T$  such that  $y > 0$  and  $My \geq 0$ .<sup>5</sup>

<sup>5</sup> The former condition may be rewritten as  $\sup\{\alpha \in \mathbb{R} \mid \exists y \geq 0 \text{ s.t. } \forall t \in \{1, \dots, T\}, (My)_t \geq \alpha \wedge y_t \leq 1\} > 0$ , and the latter may be rewritten as  $\sup\{\sum_{t=1}^T y_t \mid y \in \mathbb{R}^T, My \geq 0 \wedge \forall t \in \{1, \dots, T\}, y_t \leq 1\} > 0$ . As linear-programming problems, these may be verified in time polynomial in the size of the matrix using the methods described in e.g. Roos, Terlaky, and Vial (2006).

**Definition 6 ((Strictly) Semi-monotone)**

A matrix  $M \in \mathbb{R}^{T \times T}$  is called **strictly semi-monotone** if each of its principal sub-matrices is an **S-matrix**.  $M$  is called **semi-monotone** if each of its principal sub-matrices is an **S<sub>0</sub>-matrix**.

**Definition 7 ((Strictly) Copositive)**

A matrix  $M \in \mathbb{R}^{T \times T}$  is called **strictly copositive** if  $M + M'$  is strictly semi-monotone. If  $M + M'$  is semi-monotone then  $M$  is called **copositive**.<sup>6</sup>

**Definition 8 (Sufficient matrices)**

Let  $M \in \mathbb{R}^{T \times T}$ .  $M$  is called **column sufficient** if  $M$  is a  $P_0$ -matrix, and for each principal sub-matrix  $W := [M_{i,j}]_{i,j=k_1,\dots,k_S}$  of  $M$ , with zero determinant, and for each proper principal sub-matrix  $[W_{i,j}]_{i,j=l_1,\dots,l_R}$  of  $W$  ( $R < S$ ), with zero determinant, the columns of  $[W_{i,j}]_{i=1,\dots,S, j=l_1,\dots,l_R}$  do not form a basis for the column space of  $W$ .<sup>7</sup>

$M$  is called **row sufficient** if  $M'$  is column sufficient.  $M$  is called **sufficient** if it is column sufficient and row sufficient.

Cottle, Pang, and Stone (2009) note the following relationships between these classes (amongst others):

1. All general positive semi-definite matrices are copositive and sufficient.
2.  $P_0$  includes skew-symmetric matrices, general positive semi-definite matrices, sufficient matrices and  $P$ -matrices.
3. All  $P_0$ -matrices, and all copositive matrices are semi-monotone, and all  $P$ -matrices, and all strictly copositive matrices are strictly semi-monotone.

Additionally, from considering the  $1 \times 1$  principal sub-matrices of  $M$ , we have the following restrictions on the diagonal of  $M$ :

4. All general positive semi-definite, semi-monotone, sufficient,  $P_0$  and copositive matrices have non-negative diagonals, and all general positive definite, strictly semi-monotone,  $P$  and strictly copositive matrices have strictly positive diagonals.

For many models encountered in macroeconomics, this simple condition is already sufficient to rule out membership of these matrix classes, as medium-scale DSGE models (including, for example, Smets and Wouters (2003), as we will show in section 2.2.3) frequently have negative elements on the diagonal of the  $M$  matrix coming from the zero lower bound on nominal interest rates, when  $T$  is large enough. Unfortunately, for all of these matrix classes except the classes of general positive (semi-)definite matrices, and  $S_{(0)}$ -matrices, no algorithm which runs in an amount of time that is polynomial in  $T$  is known, thus verifying class membership may not be feasible with large  $T$ . However, disproving class membership only requires finding one principal sub-matrix which fails to have the required property, and for this, starting with the  $1 \times 1$  principal sub-matrices (e.g. the diagonal), then considering the  $2 \times 2$  ones (etc.) is often a good strategy. The facts that all of the eigenvalues of a  $T \times T$   $P$ -matrix have complex arguments in the interval  $(-\pi + \frac{\pi}{T}, \pi - \frac{\pi}{T})$ , and all of the eigenvalues of a  $T \times T$   $P_0$ -matrix have complex arguments in the interval  $[-\pi + \frac{\pi}{T}, \pi - \frac{\pi}{T}]$  (Fang 1989) may also assist in ruling out these matrix classes.

<sup>6</sup> Väliäho (1986) contains an alternative characterisation which ought to be faster to check, since it avoids solving any linear programming problems.

<sup>7</sup> Again, this may be checked via the singular value decomposition.



### 2.1.4. Existence results

We start by considering necessary or sufficient conditions for the existence of a solution to a model with occasionally binding constraints. Ideally, we would like the solution to exist for any possible path the bounded variable might have taken in the future were there no occasionally binding constraint, i.e. for any possible  $q$ . To see this, note that under a perfect foresight exercise we are ignoring the fact that shocks might hit the economy in future. More properly, we ought to integrate over future uncertainty, as in the stochastic extended path approach of Adjemian and Juillard (2013). A crude way to do this would just be to draw lots of samples of future shocks for periods  $1, \dots, S$ , and average over these draws. But in a linear model with shocks with unbounded support, providing at least one shock has an impact on a given variable, then the distribution of future paths of that variable has positive support over the entirety of  $\mathbb{R}^S$ . Thus, ideally we would like  $M$  to be such that for any  $q$ , the linear complementarity problem  $(q, M)$  has a solution.

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#### *Definition 9 (Feasible LCP)*

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Suppose  $q \in \mathbb{R}^T$  and  $M \in \mathbb{R}^{T \times T}$  are given. The LCP corresponding to  $M$  and  $q$  is called **feasible** if there exists  $y \in \mathbb{R}^T$  such that  $y \geq 0$  and  $q + My \geq 0$ .

---

By construction, if an LCP  $(q, M)$  has a solution, then it is feasible, i.e. being feasible is a necessary condition for existence. Checking feasibility is straightforward for any particular  $(q, M)$ , since to find a feasible solution we just need to solve a standard linear programming problem, which is possible in an amount of time that is polynomial in  $T$ .

---

#### *Proposition 3*

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The LCP  $(q, M)$  is feasible for all  $q \in \mathbb{R}^T$  if and only if  $M$  is an S-matrix. (Cottle, Pang, and Stone 2009)<sup>8</sup>

---

This gives an easily verified necessary condition for the global existence of a solution to the model with occasionally binding constraints. We now turn to sufficient conditions.

---

#### *Proposition 4*

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The LCP  $(q, M)$  is solvable if it is feasible and, either:

1.  $M$  is row-sufficient, or,
2.  $M$  is copositive and for all non-singular principal sub-matrices  $W := [M_{i,j}]_{i,j=k_1, \dots, k_S}$  of  $M$ , all non-negative columns of  $W^{-1}$  possess a non-zero diagonal element.

(Cottle, Pang, and Stone 2009; Väliaho 1986)

---

If either condition 1 or condition 2 of Proposition 4 is satisfied, then to check existence for any particular  $q$ , we only need to solve a linear programming problem to see if a solution exists for a particular  $q$ . As this may be substantially faster than solving the LCP, this may be helpful in practice.

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<sup>8</sup> All of the results on LCPs in both this and the following section are restatements of (assorted) results contained in Cottle, Pang, and Stone (2009) and Väliaho (1986) (for the characterisation of “copositive-plus” matrices), and the reader is referred to those works for proofs and further references. Cottle, Pang, and Stone (2009) also contains many additional necessary or sufficient conditions for the various properties of interest.

**Proposition 5**

The LCP  $(q, M)$  is solvable for all  $q \in \mathbb{R}^T$ , if at least one of the following conditions holds:

1.  $M$  is an S-matrix, and either condition 1 or condition 2 of Proposition 4 are satisfied.
2.  $M$  is copositive and non-degenerate.
3.  $M$  is a P-matrix, a strictly copositive matrix or a strictly semi-monotone matrix.

(Cottle, Pang, and Stone 2009)

If condition 1, 2 or 3 of Proposition 5 is satisfied, then we know that the LCP will always have a solution. Therefore, for any path of the bounded variable in the absence of the bound, we will be able to solve the model even with the bound. Since it is unclear what happens in a New-Keynesian model when there is no solution that imposes the zero lower bound on nominal interest rates, monetary policy makers should always choose a policy rule that produces a model that satisfies one of these three conditions, if they can.

Ideally, we might have liked conditions for the existence of a solution that are both necessary and sufficient, but unfortunately at present no such conditions exist in full generality. However, in the special case of  $M$  matrices with nonnegative entries, we have the following result:

**Proposition 6**

If  $M$  is a matrix with nonnegative entries, then the LCP  $(q, M)$  is solvable for all  $q \in \mathbb{R}^T$ , if and only if  $M$  has a strictly positive diagonal. (Cottle, Pang, and Stone 2009)

**2.1.5. Uniqueness results**

While no fully general necessary and sufficient conditions have been derived for existence, such conditions have been derived for the existence of a unique solution, in particular:

**Proposition 7**

The LCP  $(q, M)$  has a unique solution for all  $q \in \mathbb{R}^T$ , if and only if  $M$  is a P-matrix. (Samelson, Thrall, and Wesler 1958; Cottle, Pang, and Stone 2009)

This proposition is the equivalent for models with occasionally binding constraints of the key proposition of Blanchard and Kahn (1980). By testing whether our matrix  $M$  is a P-matrix we can immediately determine if the model possesses a unique solution in any state of the world, and for any sequence of future shocks. In our experience, this condition is frequently satisfied in efficient models, such as models of irreversible investment, but is not generally satisfied in medium-scale New-Keynesian models with a zero lower bound on nominal interest rates.

Since some classes of models almost never possess a unique solution when at the zero lower bound, we might reasonably require a lesser condition, namely that at least when the solution to the model without a bound is a solution to the model with the bound (i.e. when the solution to Problem 1 is a solution to Problem 2), then it ought to be the unique solution. This is equivalent to requiring that when  $q$  is non-negative, the LCP  $(q, M)$  has a unique solution. Conditions for this are given in the following propositions:

**Proposition 8**

The LCP  $(q, M)$  has a unique solution for all  $q \in \mathbb{R}^T$  with  $q \gg 0$  if and only if  $M$  is semi-monotone. (Cottle, Pang, and Stone 2009)

**Proposition 9**

The LCP  $(q, M)$  has a unique solution for all  $q \in \mathbb{R}^T$  with  $q \geq 0$  if and only if  $M$  is strictly semi-monotone. (Cottle, Pang, and Stone 2009)

Hence, by verifying that  $M$  is (strictly) semi-monotone, we can reassure ourselves that merely introducing the bound will not change the solution away from the bound. When this condition is violated, even when the economy is a long way from the bound, there may be solutions which jump to the bound.

**2.1.6. Properties of the solution set**

Where there are multiple solutions, we might like to be able to select one via some objective function. This is particularly tractable when either the number of solutions is finite, or the solution set is convex. Conditions for this are given in the following propositions:

**Proposition 10**

The LCP  $(q, M)$  has a finite (possibly zero) number of solutions for all  $q \in \mathbb{R}^T$  if and only if  $M$  is non-degenerate. (Cottle, Pang, and Stone 2009)

**Proposition 11**

The LCP  $(q, M)$  has a convex (possibly empty) set of solutions for all  $q \in \mathbb{R}^T$  if and only if  $M$  is column sufficient. (Cottle, Pang, and Stone 2009)

**2.1.7. Generalisations to richer otherwise linear models**

It is straightforward to generalise these results for Problem 2 to less restrictive otherwise linear models with occasionally binding constraints.

Firstly, if the constraint is on a variable other than  $x_{1,t}$ , or in another equation than the first, then it is immediately clear that all of the results must go through as before (just by relabelling and rearranging). Furthermore, if the constraint takes the form of  $z_{1,t} = \max\{z_{2,t}, z_{3,t}\}$ , where  $z_{1,t}$ ,  $z_{2,t}$  and  $z_{3,t}$  are linear expressions in the contemporaneous values, lags and leads of  $x_t$ , then, assuming without loss of generality that  $z_{3,\cdot} > z_{2,\cdot}$  in steady-state, we have that:

$$z_{1,t} - z_{2,t} = \max\{0, z_{3,t} - z_{2,t}\}.$$

Hence, adding a new auxiliary variable  $x_{n+1,t}$ , with the associated equation:

$$x_{n+1,t} = z_{1,t} - z_{2,t},$$

and replacing the constrained equation with:

$$x_{n+1,t} = \max\{0, z_{3,t} - z_{2,t}\},$$

we have a new equation in the form covered by our original results. Moreover, if rather than a max we have a min, we just use the fact that if  $z_{1,t} = \min\{z_{2,t}, z_{3,t}\}$ , then  $-z_{1,t} = \max\{-z_{2,t}, -z_{3,t}\}$ , which is in the form covered by the generalisation just established.

We may also readily deal with multiple occasionally binding constraints, following the representation used in Holden & Paetz (2012). Suppose there are  $c$  constrained variables in the model. For  $a \in \{1, \dots, c\}$ , let  $q^{(a)}$  be the path of the  $a^{\text{th}}$  constrained variable in the absence of all constraints. For  $a, b \in \{1, \dots, c\}$ , let  $M^{(a,b)}$  be the

matrix created by horizontally stacking the column vector relative impulse responses of the  $a^{\text{th}}$  constrained variable to magnitude 1 news shocks at horizon  $0, \dots, T-1$  to the equation defining the  $b^{\text{th}}$  constrained variables. For example, if  $c = 1$  so there is a single constraint, then we would have that  $M^{(1,1)} = M$  as defined in equation (1). Finally, let:

$$q := \begin{bmatrix} q^{(1)} \\ \vdots \\ q^{(c)} \end{bmatrix}, \quad M := \begin{bmatrix} M^{(1,1)} & \dots & M^{(1,c)} \\ \vdots & \ddots & \vdots \\ M^{(c,1)} & \dots & M^{(c,c)} \end{bmatrix},$$

and let  $y$  be a solution to the LCP  $(q, M)$ . Then the vertically stacked paths of the constrained variables in a solution which satisfies these constraints is given by  $q + My$ , and again any solution satisfying the constraints corresponds to a solution to the LCP. Thus, in the multiple constraint case, all of our previous results go through, with this redefined  $q$  vector and  $M$  matrix.

## 2.2. Select examples

Brendon, Paustian, and Yates (2015) consider multiple equilibria in a simple New Keynesian model with an output growth rate term in the Taylor rule. They show that with sufficiently large reaction to the growth rate, there can be multiple equilibria today, even when the policy rule used to form tomorrow's expectations is held fixed. This is equivalent to the existence of multiple equilibria even when  $T = 1$ . In the first sub-section here, we give an alternative analytic proof of this using our results, and discuss the generalisation to higher  $T$ . We refer the reader to the original paper for an elegant discussion of the intuition behind these results.

Brendon, Paustian, and Yates (2015) go on to show numerical results from the model with persistence in the shadow nominal interest rate (i.e. the rate which would obtain were it not for the zero lower bound). In the second sub-section here we numerically examine this case with larger  $T$ , illustrating how multiple equilibria tend to become easier to support when  $T$  is large. We conclude by examining the  $M$  matrices generated by the posterior-modes of the Smets and Wouters (2003) and Smets and Wouters (2007) models, illustrating that problems of multiplicity are not confined to carefully constructed theoretical examples.

### 2.2.1. The simple Brendon, Paustian, and Yates (2015) model

The equations of the simple Brendon, Paustian, and Yates (2015) model are as follows:

$$\begin{aligned} x_{i,t} &= \max\{0, 1 - \beta + \alpha_{\Delta y}(x_{y,t} - x_{y,t-1}) + \alpha_{\pi}x_{\pi,t}\}, \\ x_{y,t} &= \mathbb{E}_t x_{y,t+1} - \frac{1}{\sigma}(x_{i,t} + \beta - 1 - \mathbb{E}_t x_{\pi,t+1}), \\ x_{\pi,t} &= \beta \mathbb{E}_t x_{\pi,t+1} + \gamma x_{y,t}, \end{aligned}$$

where  $x_{i,t}$  is the nominal interest rate,  $x_{y,t}$  is the deviation of output from steady-state,  $x_{\pi,t}$  is the deviation of inflation from steady-state, and  $\beta \in (0,1)$ ,  $\gamma, \sigma, \alpha_{\Delta y} \in (0, \infty)$ ,  $\alpha_{\pi} \in (1, \infty)$  are parameters. Defining  $x_t = [x_{i,t} \ x_{y,t} \ x_{\pi,t}]'$ , this is in the form of Problem 2, with:

$$A := \begin{bmatrix} 0 & -\alpha_{\Delta y} & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad B := \begin{bmatrix} -1 & \alpha_{\Delta y} & \alpha_{\pi} \\ -\frac{1}{\sigma} & -1 & 0 \\ 0 & \gamma & -1 \end{bmatrix}, \quad C := \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & \frac{1}{\sigma} \\ 0 & 0 & \beta \end{bmatrix}.$$

Let  $f := F_{2,2}$ , where  $F$  is as in Assumption 1. Then:

$$F = \begin{bmatrix} 0 & \alpha_{\Delta y}(f-1) + \alpha_{\pi} \frac{\gamma f}{1-\beta f} & 0 \\ 0 & f & 0 \\ 0 & \frac{\gamma f}{1-\beta f} & 0 \end{bmatrix}.$$

Hence:

$$f = f^2 - \frac{1}{\sigma} \left( \alpha_{\Delta y}(f-1) + \alpha_{\pi} \frac{\gamma f}{1-\beta f} - \frac{\gamma f^2}{1-\beta f} \right),$$

i.e.:

$$\beta \sigma f^3 - \left( (\alpha_{\Delta y} + \sigma)\beta + \gamma + \sigma \right) f^2 + \left( (1 + \beta)\alpha_{\Delta y} + \gamma\alpha_{\pi} + \sigma \right) f - \alpha_{\Delta y} = 0. \quad (3)$$

When  $f \leq 0$ , the left hand side is negative, and when  $f = 1$ , the left hand side equals  $(\alpha_{\pi} - 1)\gamma > 0$  (by assumption on  $\alpha_{\pi}$ ), hence equation (3) has either one or three solutions in  $(0,1)$ , and no solutions in  $(-\infty, 0]$ . We wish to prove there is a unique solution in  $(-1,1)$ . First note that when  $\alpha_{\pi} = 1$ , the discriminant of the polynomial is:

$$\left( (1 - \beta)(\alpha_{\Delta y} - \sigma) - \gamma \right)^2 \left( (\beta\alpha_{\Delta y})^2 + 2\beta(\gamma - \sigma)\alpha_{\Delta y} + (\gamma + \sigma)^2 \right).$$

The first multiplicand is positive. The second is minimised when  $\sigma = \beta\alpha_{\Delta y} - \gamma$ , at the value  $4\beta\gamma\alpha_{\Delta y} > 0$ , hence this multiplicand is positive too. Consequently, at least for small  $\alpha_{\pi}$ , there are three real solutions for  $f$ , so there may be multiple solutions in  $(0,1)$ . In the appendix, section 7.1, we prove that there is a unique solution to equation (3) in  $(-1,1)$ , establishing that Assumption 1 holds.

Now, when  $T = 1$ ,  $M$  is equal to the top left element of the matrix  $-(B + CF)^{-1}$ , i.e.:

$$M = \frac{\beta \sigma f^2 - ((1 + \beta)\sigma + \gamma)f + \sigma}{\beta \sigma f^2 - ((1 + \beta)\sigma + \gamma + \beta\alpha_{\Delta y})f + \sigma + \alpha_{\Delta y} + \gamma\alpha_{\pi}}.$$

Now, multiplying the denominator by  $f$  gives:

$$\begin{aligned} & \beta \sigma f^3 - \left( (1 + \beta)\sigma + \gamma + \beta\alpha_{\Delta y} \right) f^2 + (\sigma + \alpha_{\Delta y} + \gamma\alpha_{\pi})f \\ &= \left[ \beta \sigma f^3 - \left( (\alpha_{\Delta y} + \sigma)\beta + \gamma + \sigma \right) f^2 + \left( (1 + \beta)\alpha_{\Delta y} + \gamma\alpha_{\pi} + \sigma \right) f - \alpha_{\Delta y} \right] - [\beta\alpha_{\Delta y}f - \alpha_{\Delta y}] \\ &= (1 - \beta f)\alpha_{\Delta y} > 0, \end{aligned}$$

by equation (3). Hence, the sign of  $M$  is that of  $\beta \sigma f^2 - ((1 + \beta)\sigma + \gamma)f + \sigma$ . I.e.,  $M$  is negative if and only if:

$$\frac{((1 + \beta)\sigma + \gamma) - \sqrt{((1 + \beta)\sigma + \gamma)^2 - 4\beta\sigma^2}}{2\beta\sigma} < f < \frac{((1 + \beta)\sigma + \gamma) + \sqrt{((1 + \beta)\sigma + \gamma)^2 - 4\beta\sigma^2}}{2\beta\sigma}.$$

The upper limit is greater than 1, so only the lower is relevant. To translate this bound on  $f$  into a bound on  $\alpha_{\Delta y}$ , we first need to establish that  $f$  is monotonic in  $\alpha_{\Delta y}$ . Totally differentiating equation (3) gives:

$$\left[ 3\beta\sigma f^2 - 2 \left( (\alpha_{\Delta y} + \sigma)\beta + \gamma + \sigma \right) f + \left( (1 + \beta)\alpha_{\Delta y} + \gamma\alpha_{\pi} + \sigma \right) \right] \frac{df}{d\alpha_{\Delta y}} = (1 - \beta f)(1 - f) > 0.$$

Thus, the sign of  $\frac{df}{d\alpha_{\Delta y}}$  is equal to that of:

$$3\beta\sigma f^2 - 2 \left( (\alpha_{\Delta y} + \sigma)\beta + \gamma + \sigma \right) f + \left( (1 + \beta)\alpha_{\Delta y} + \gamma\alpha_{\pi} + \sigma \right).$$

Note, however, that this expression is just the derivative of the left hand side of equation (3) with respect to  $f$ .

To establish the sign of  $\frac{df}{d\alpha_{\Delta y}}$ , we consider two cases. First, suppose that equation (3) has three real solutions. Then, the unique solution to equation (3) in  $(0,1)$  is its lowest solution. Hence, this solution must be below the first local maximum of the left hand side of equation (3). Consequently, at the  $f \in (0,1)$ , which solves equation (3),  $3\beta\sigma f^2 - 2((\alpha_{\Delta y} + \sigma)\beta + \gamma + \sigma)f + ((1 + \beta)\alpha_{\Delta y} + \gamma\alpha_{\pi} + \sigma) > 0$ . Alternatively, suppose that equation (3) has a unique real solution. Then the left hand side of this equation cannot change sign in between its local maximum and its local minimum (if it has any). Thus, at the  $f \in (0,1)$  at which it changes sign, we must have that  $3\beta\sigma f^2 - 2((\alpha_{\Delta y} + \sigma)\beta + \gamma + \sigma)f + ((1 + \beta)\alpha_{\Delta y} + \gamma\alpha_{\pi} + \sigma) > 0$ . Therefore, in either case  $\frac{df}{d\alpha_{\Delta y}} > 0$ , meaning that  $f$  is monotonic increasing in  $\alpha_{\Delta y}$ .

Consequently, to find the critical  $(f, \alpha_{\Delta y})$  at which  $M$  changes sign, it is sufficient to find the lowest solution with respect to both  $f$  and  $\alpha_{\Delta y}$  of the pair of equations:

$$\begin{aligned}\beta\sigma f^2 - ((1 + \beta)\sigma + \gamma)f + \sigma &= 0, \\ \beta\sigma f^3 - ((\alpha_{\Delta y} + \sigma)\beta + \gamma + \sigma)f^2 + ((1 + \beta)\alpha_{\Delta y} + \gamma\alpha_{\pi} + \sigma)f - \alpha_{\Delta y} &= 0.\end{aligned}$$

The former implies that:

$$\beta\sigma f^3 - ((1 + \beta)\sigma + \gamma)f^2 + \sigma f = 0,$$

so, by the latter:

$$\alpha_{\Delta y}\beta f^2 - ((1 + \beta)\alpha_{\Delta y} + \gamma\alpha_{\pi})f + \alpha_{\Delta y} = 0.$$

If  $\alpha_{\Delta y} = \sigma\alpha_{\pi}$ , then this equation holds if and only if:

$$\sigma\beta f^2 - ((1 + \beta)\sigma + \gamma)f + \sigma = 0.$$

Therefore, the critical  $(f, \alpha_{\Delta y})$  at which  $M$  changes sign are given by:

$$\begin{aligned}\alpha_{\Delta y} &= \sigma\alpha_{\pi}, \\ f &= \frac{((1 + \beta)\sigma + \gamma) - \sqrt{((1 + \beta)\sigma + \gamma)^2 - 4\beta\sigma^2}}{2\beta\sigma}.\end{aligned}$$

Thus,  $M$  is negative if and only if  $\alpha_{\Delta y} > \sigma\alpha_{\pi}$ , and  $M$  is zero if and only if  $\alpha_{\Delta y} = \sigma\alpha_{\pi}$ .

For a  $1 \times 1$  matrix, checking the conditions from section 2.1.3 is trivial. In particular, we have that if  $\alpha_{\Delta y} < \sigma\alpha_{\pi}$ , then  $M$  is a general positive definite, strictly semi-monotone, strictly co-positive, sufficient, P, S matrix, if  $\alpha_{\Delta y} \leq \sigma\alpha_{\pi}$ , then  $M$  is a general positive semi-definite, semi-monotone, co-positive, sufficient,  $P_0$ ,  $S_0$  matrix, if  $\alpha_{\Delta y} = \sigma\alpha_{\pi}$ , then  $M$  is degenerate, and if  $\alpha_{\Delta y} \neq \sigma\alpha_{\pi}$ , then  $M$  is non-degenerate. Hence, when  $T = 1$ , if  $\alpha_{\Delta y} < \sigma\alpha_{\pi}$  then the model has a unique solution for all  $q$ , if  $\alpha_{\Delta y} \leq \sigma\alpha_{\pi}$  then the model has a convex set of solutions for all  $q$ , a unique solution whenever  $q > 0$ , and at least one solution when  $q = 0$ . When  $\alpha_{\Delta y} > \sigma\alpha_{\pi}$ , then  $M$  is negative, and so for any positive  $q$ , there exists  $y > 0$  such that  $q + My = 0$ , so the model has multiple solutions in this case. I.e. there are solutions which jump to the bound, even when the nominal interest rate would always be positive were there no bound at all.

When  $T > 1$ , the previous results imply that if  $\alpha_{\Delta y} > \sigma\alpha_{\pi}$ , then  $M$  is neither  $P_0$ , general positive semi-definite, semi-monotone, co-positive, nor sufficient, since the top-left  $1 \times 1$  principal sub-matrix of  $M$  is the same as it is when  $T = 1$ . Thus, if anything, when  $T > 1$ , the parameter region in which there are multiple solutions (when away from the bound or at it) is larger. However, numerical experiments suggest that this parameter region in fact remains the same as  $T$  increases, which is unsurprising given the weak persistence

of this model. Thus, if we want more interesting results with higher  $T$ , we need to consider a model with a stronger persistence mechanism.

### 2.2.2. The Brendon, Paustian, and Yates (2015) model with shadow interest rate persistence

If we introduce persistence in the shadow interest rate to the previous model, we obtain the following equations:

$$\begin{aligned} x_{i,t} &= \max\{0, x_{d,t}\}, \\ x_{d,t} &= (1 - \rho)(1 - \beta + \alpha_{\Delta y}(x_{y,t} - x_{y,t-1}) + \alpha_{\pi}x_{\pi,t}) + \rho x_{d,t-1}, \\ x_{y,t} &= \mathbb{E}_t x_{y,t+1} - \frac{1}{\sigma}(x_{i,t} + \beta - 1 - \mathbb{E}_t x_{\pi,t+1}), \\ x_{\pi,t} &= \beta \mathbb{E}_t x_{\pi,t+1} + \gamma x_{y,t}, \end{aligned}$$

where parameters and variables are as before, with the addition of  $x_{d,t}$ , the shadow nominal interest rate, and  $\rho$ , its persistence. Defining  $x_t = [x_{i,t} \ x_{d,t} \ x_{y,t} \ x_{\pi,t}]'$ , this is again in the form of Problem 2, with:

$$A := \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & \rho & -(1 - \rho)\alpha_{\Delta y} & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \quad B := \begin{bmatrix} -1 & 1 & 0 & 0 \\ 0 & -1 & (1 - \rho)\alpha_{\Delta y} & (1 - \rho)\alpha_{\pi} \\ -\frac{1}{\sigma} & 0 & -1 & 0 \\ 0 & 0 & \gamma & -1 \end{bmatrix}, \quad C := \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & \frac{1}{\sigma} \\ 0 & 0 & 0 & \beta \end{bmatrix}.$$

In all of the following, we set  $\sigma = 1$ ,  $\beta = 0.99$ ,  $\gamma = \frac{(1-0.85)(1-\beta(0.85))}{0.85}(2 + \sigma)$ ,  $\rho = 0.5$ , following Brendon, Paustian, and Yates (2015). For each considered  $\alpha_{\Delta y}$ ,  $\alpha_{\pi}$ , we verify numerically that Assumption 1 is indeed satisfied.

In Figure 1, we plot the regions in  $(\alpha_{\Delta y}, \alpha_{\pi})$  space in which  $M$  is a P-matrix (P<sub>0</sub>-matrix) when  $T = 2$  or  $T = 4$ . For this model, these correspond to the regions in which  $M$  is strictly semi-monotone (semi-monotone). As may be seen, in the smaller  $T$  case, the P-matrix region is much larger. This relationship appears to continue to hold for both larger and smaller  $T$ , with the equivalent  $T = 1$  plot being almost entirely shaded, and the large  $T$  plot apparently tending to the equivalent plot from the model without monetary policy persistence. Intuitively, the persistence in the shadow nominal interest rate dampens the immediate response of nominal interest rates to inflation and output growth, making it harder to induce a zero lower bound episode over short-horizons.

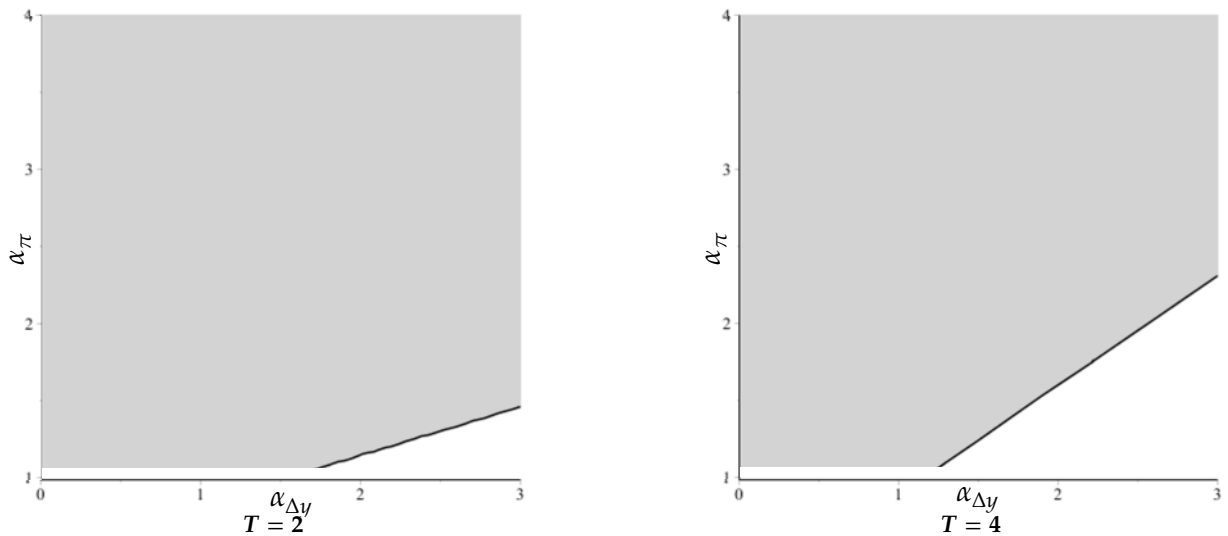


Figure 1: Regions in which  $M$  is a P-matrix (shaded grey) or a P<sub>0</sub>-matrix (shaded grey, plus the black line), when  $T = 2$  (left) or  $T = 4$  (right).

### 2.2.3. The Smets and Wouters (2003) and Smets and Wouters (2007) models

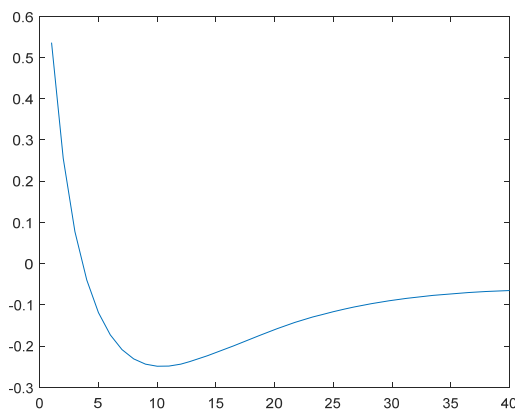
Smets and Wouters (2003) and Smets and Wouters (2007) are the canonical medium-scale linear DSGE models, featuring assorted shocks, habits, price and wage indexation, capital (with adjustment costs), (costly) variable utilisation and quite general monetary policy reaction functions. The former model is estimated on Euro area data, while the latter is estimated on US data. The latter model also contains trend growth (permitting its estimation on non-detrended data), and a slightly more general aggregator across industries. However, overall, they are really quite similar models, and any differences in their behaviour chiefly stems from differences in the estimated parameters. Since both models are incredibly well known in the literature, we omit their equations here, referring the reader to the original papers for further details.

To assess the likelihood of multiple equilibria at or away from the zero lower bound, we augment each model with a zero lower bound on nominal interest rates, and evaluate the properties of each model's  $M$  matrix with large  $T$ , at the estimated posterior-modes from the original papers. Note that we do not introduce an auxiliary for shadow nominal interest rates, so the monetary rules take the form of:

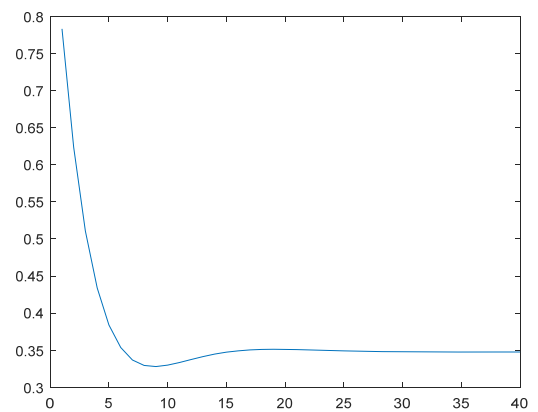
$$r_t = \max\{0, (1 - \rho)(\dots) + \rho r_{t-1} + \dots\}$$

in both cases.

As discussed in section 2.1.3, if the diagonal of the  $M$  matrix ever goes negative, then the  $M$  matrix cannot be general positive semi-definite, semi-monotone, sufficient,  $P_0$  or copositive, and hence the model will sometimes have multiple solutions even when away from the zero lower bound (i.e. for some strictly positive  $q$ ). In Figure 2, we plot the diagonal of the  $M$  matrix for each model in turn, i.e. the impact on nominal interest rates in period  $t$  of news in period 1 that a positive, magnitude one shock will hit nominal interest rates in period  $t$ . Immediately, we see that while in the US model, these impacts remain positive at all horizons, in the Euro area model, these impacts turn negative after just a few periods, and remain so at least up to period 40. Therefore, in the zero lower bound augmented Smets and Wouters (2003) model, there is not always a unique equilibrium. Furthermore, there are sequences of predicted future shocks (with positive density) for which the model without the zero lower bound would always feature positive interest rates, but for which the model with the zero lower bound could hit zero.



The Smets and Wouters (2003) model



The Smets and Wouters (2007) model

Figure 2: The diagonals of the  $M$  matrices for the Smets and Wouters (2003) and Smets and Wouters (2007) models

It remains for us to assess whether  $M$  is a  $P_0$ -matrix or (strictly) semi-monotone for the Smets and Wouters (2007) model. Numerical calculations reveal that for  $T < 9$ ,  $M$  is a  $P$ -matrix, and hence is strictly semi-monotone. However, with  $T \geq 9$ ,  $M$  contains a  $6 \times 6$  principal sub-matrix (with indices 1,2,4,6,7,9) with



negative determinant, which is neither an  $S$  nor an  $S_0$ -matrix. Thus, for  $T \geq 9$ ,  $M$  is not a  $P_{(0)}$ -matrix or (strictly) semi-monotone, and hence this model also has multiple equilibria, even when away from the bound. Given that the US has been at the zero lower bound for over eight years, that  $T$  ought to be greater than eight quarters seems pretty uncontroversial. Hence, in both the Euro area and the US, we ought to take seriously the possibility that the existence of the zero lower bound produces non-uniqueness.

## 2.3. Algorithms for the otherwise linear case

### 2.3.1. On the difficulty of the problem

We start with a note of caution. If no properties of the matrix  $M$  are known a priori, then Problem 4 is provably a computationally difficult problem, more formally, it may be shown to be “strongly-NP complete” (Chung 1989), and this remains true even if  $M$  is restricted to be a  $P_0$  matrix (Kojima et al. 1991). This means that even if the inputs  $q$  and  $M$  have descriptions which are of a polynomial length in  $T$ , then if we could solve Problem 4 in an amount of time that was polynomial in  $T$ , then we could also solve in polynomial time any problem for which the solution could be verified in polynomial time. In the language of computer science, this would mean that “ $P=NP$ ”, something almost all computer scientists believe to be false. The strength of computer scientists conviction that this is not true is best exemplified by the fact that were  $P=NP$ , all commonly used forms of cryptography (such as those used to secure internet banking), would be defeated.

Since there is a bijection between solutions for Problem 4 and solutions for Problem 2, this means that while forming expectations in linear models without occasionally binding constraints is computationally easy (polynomial algorithms exist for it), in models with occasionally binding constraints, forming expectations may be incredibly difficult. It also means that we should be sceptical of claims of computational efficiency from other algorithms for solving models with occasionally binding constraints. A proof that such algorithms actually ran in time polynomial either in  $T$  or in the number of state variables of the model, on all models, would again function as a proof that “ $P=NP$ ”, since we showed in Proposition 2 that there is a model corresponding to any  $T \times T$   $M$  matrix, featuring polynomial in  $T$  state variables. Thus, for example, global methods will never escape the curse of dimensionality in general models with occasionally binding constraints, even using methods explicitly designed to do this such as that of Judd, Maliar, and Maliar (2012). In fact, even proving the finiteness of algorithms for solving these problems is non-trivial (see e.g. Csizmadia and Illés 2006), and, for example, there is no reason to believe that the iterations in Guerrieri and Iacoviello (2015) will converge in finite time on all models.

For some special classes though, it has been shown that the problem is solvable in polynomial time in  $T$ . In particular, if  $M$  is general positive semi-definite, then this is possible (Kojima, Mizuno, and Yoshise 1989). However, it appears that  $M$  is general positive semi-definite in only very few macroeconomic models. Furthermore, if either condition 1 or condition 2 of Proposition 4 is known to be satisfied (e.g.  $M$  is row sufficient), then we can find out if a solution exists in polynomial time, by solving the feasibility problem.

Moreover, a polynomial time algorithm exists (Illés, Nagy, and Terlaky 2010) which will give a certificate that one of the following is true, for a given  $q$  and real number  $\bar{\kappa} \geq 0$ :

- For any  $\kappa \leq \bar{\kappa}$ ,  $M$  is not a member of the matrix class  $P^*(\kappa)$ , defined in the paper. (Note that for  $\kappa_1 < \kappa_2$ ,  $P^*(\kappa_1) \subseteq P^*(\kappa_2)$ , and that the class of sufficient matrices is the union of the classes of  $P^*(\kappa)$  matrices for all  $\kappa \geq 0$ .)
- The LCP  $(q, M)$  has no solution.
- The LCP  $(q, M)$  has the solution  $y$ .

Thus for “most” sufficient matrices we can find a solution (or a certificate that there is none), in polynomial time. It has been conjectured that in fact this holds for all sufficient matrices (Fukuda 2015).

Unfortunately, no algorithm is known for finding out if  $M$  is sufficient in polynomial time. Indeed, it has also been shown (Coxson 1994; Tseng 2000) that it is “co-NP complete” to test any of the following:

- $M$  is non-degenerate.
- $M$  is a P-matrix.
- $M$  is a  $P_0$ -matrix.
- $M$  is semi-monotone.
- $M$  is strictly semi-monotone.
- $M$  is column sufficient.
- $M$  is row sufficient.

This means that were a polynomial time (in  $T$ ) algorithm available for these things then we would have a proof that  $P=NP$ . Likewise, were a polynomial time (in  $T$ ) algorithm available for testing if a particular model, e.g.:

- always had a unique solution,
- always had a unique solution when away from the bound,
- always had a finite number of solutions,
- always had a convex set of solutions,

then that algorithm would also serve as a proof that  $P=NP$ , since we showed in Proposition 2 that a model could be constructed which produces any given  $M$  matrix. Since the model we constructed to match a  $T \times T$   $M$  matrix featured polynomial in  $M$  state variables, this also means that an algorithm which answered these questions which ran in an amount of time polynomial in the number of state variables would also serve as a proof that  $P=NP$ .

### 2.3.2. The mixed integer linear programming representation

Given that there is no reason to believe that there is a polynomial time algorithm to solve the LCPs we encounter, it is important that we choose an algorithm, which, although it may not complete in polynomial time in the worst case, is nonetheless as computationally efficient as possible, particularly on average. One way to do this is to reduce the problem of finding an LCP to the solution of a problem for which highly efficient algorithms and computational libraries are available. One such problem is mixed integer linear programming (MILP), for which algorithms are included in most major optimisation suites (e.g. CPLEX, Gurobi, XPress MP, MOKEK, etc.). Conveniently, we can reduce the LCP problem to the MILP one in a way that gives not only a solution when one exists, but also a definite answer on whether or not there is a solution. This is an improvement over more naïve approaches, such as those of Holden (2010), Holden & Paetz (2012)

or Guerrieri and Iacoviello (2015), for which a failure of convergence may just mean that the optimiser got stuck at some local minimum.

To motivate the LCP representation, suppose that  $y$  solves the LCP  $(q, M)$ . Then  $y \geq 0$ ,  $0 \leq q + My$  and if  $y_j > 0$  then  $(q + My)_j = 0$ . Now let  $\tilde{\omega} > 0$  be an arbitrary constant, let

$$\alpha := \min\{\|y\|_\infty^{-1}, \tilde{\omega}\|q + My\|_\infty^{-1}\} > 0$$

(where  $\|\cdot\|_\infty$  is the usual sup norm), let  $\hat{y} := \alpha y$ , let  $1_{T \times 1}$  be a  $T \times 1$  vector of ones, and let  $z \in \{0, 1\}^T$  be such that for all  $j \in \{1, \dots, T\}$ ,  $z_j = 1$  if and only if  $y_j > 0$ . Then  $0 \leq \hat{y} \leq 1_{T \times 1}$  and:

$$0 \leq \alpha q + M\hat{y} \leq \alpha\|q + My\|_\infty \leq \tilde{\omega}1_{T \times 1}.$$

Now, if  $z_j = 0$  for some  $j \in \{1, \dots, T\}$ , then  $y_j = 0$ . Hence, in fact,  $0 \leq \hat{y} \leq z$ . Likewise, if  $z_j = 1$ , then  $y_j > 0$ , so since  $y$  solves the LCP,  $0 = \alpha(q + My)_j = (\alpha q + M\hat{y})_j$ . Hence, similarly:

$$0 \leq \alpha q + M\hat{y} \leq \tilde{\omega}(1_{T \times 1} - z).$$

Moreover, for any  $\tilde{\alpha} > \alpha$ , we claim that there is no  $z \in \{0, 1\}^T$  such that  $0 \leq \tilde{\alpha}y \leq z$  and  $0 \leq \tilde{\alpha}q + M(\tilde{\alpha}y) \leq \tilde{\omega}(1_{T \times 1} - z)$ . To see this, suppose for a contradiction that there were. Then  $\tilde{\alpha}\|y\|_\infty \leq 1$ , so  $\alpha < \tilde{\alpha} \leq \|y\|_\infty^{-1}$ . Hence,  $\alpha = \tilde{\omega}\|q + My\|_\infty^{-1}$ . But, by assumption  $\tilde{\alpha}\|q + My\|_\infty \leq \tilde{\omega}$ , hence  $\tilde{\omega}\|q + My\|_\infty^{-1} = \alpha < \tilde{\alpha} \leq \tilde{\omega}\|q + My\|_\infty^{-1}$ , which gives the required contradiction. Therefore,  $\alpha, \hat{y}, z$  are feasible for the following MILP problem (though they may not necessarily be the solution):

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**Problem 5 (MILP representation of LCP)**

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Suppose  $\tilde{\omega} > 0$ ,  $q \in \mathbb{R}^T$  and  $M \in \mathbb{R}^{T \times T}$  are given. Find  $\alpha \in \mathbb{R}$ ,  $\hat{y} \in \mathbb{R}^T$ ,  $z \in \{0, 1\}^T$  to maximise  $\alpha$  subject to the following constraints:  $\alpha \geq 0$ ,  $0 \leq \hat{y} \leq z$ ,  $0 \leq \alpha q + M\hat{y} \leq \tilde{\omega}(1_{T \times 1} - z)$ .

---

A version of this representation with  $\tilde{\omega} = 1$  was first given by Pardalos and Rosen (1988), and its properties in that special case were proven by Rosen (1990).

We now establish that solutions of the MILP representation are solutions of the LCP. Suppose that  $\alpha, \hat{y}, z$  solve Problem 5 (MILP representation of LCP). If  $\alpha = 0$ , then there is no  $\alpha > 0$  such that  $0 \leq \hat{y} \leq z$ ,  $0 \leq \alpha q + M\hat{y} \leq \tilde{\omega}(1_{T \times 1} - z)$ . Now, we showed above that if the LCP  $(q, M)$  had a solution, then there would be an  $\alpha > 0$ ,  $\hat{y}$  and  $z$  which were feasible for Problem 5 (MILP representation of LCP), hence, this  $\alpha > 0$  provides a lower bound on the solution to Problem 5 (MILP representation of LCP). Thus, if  $\alpha = 0$ , the LCP cannot have a solution. Alternatively, suppose that  $\alpha > 0$ . Then if for some  $j \in \{1, \dots, T\}$ ,  $z_j = 1$ , then  $0 = (\alpha q + M\hat{y})_j$ , and if for some  $j \in \{1, \dots, T\}$ ,  $z_j = 0$ , then  $\hat{y}_j = 0$ . Thus,  $\hat{y} \circ (\alpha q + M\hat{y}) = 0$ . Finally, define  $y := \frac{\hat{y}}{\alpha} \geq 0$ , hence  $\hat{y} = \alpha y$ ,  $0 \leq q + My$  and  $y \circ (q + My) = 0$ , i.e.  $y$  solves the LCP  $(q, M)$ . This completes the proof of the following result:

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**Proposition 12**

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Suppose  $\tilde{\omega} > 0$ ,  $q \in \mathbb{R}^T$  and  $M \in \mathbb{R}^{T \times T}$  are given. If  $y$  solves Problem 4 (Linear Complementarity Problem (LCP)), then the solution to Problem 5 (MILP representation of LCP) has  $\alpha \geq \min\{\|y\|_\infty^{-1}, \tilde{\omega}\|q + My\|_\infty^{-1}\}$ . If the solution to Problem 4 (Linear Complementarity Problem (LCP)) is unique, then this last inequality holds with equality, and  $\hat{y} = \alpha y$ ,  $z = \begin{cases} 1 & \text{if } y_j > 0 \\ 0 & \text{if } y_j = 0 \end{cases}$  in the solution to Problem 5 (MILP representation of LCP). Conversely, if  $\alpha, \hat{y}, z$  solve Problem 5 (MILP representation of LCP), then if  $\alpha = 0$ , Problem 4 (Linear Complementarity Problem (LCP)) has no solution, and if  $\alpha > 0$ , then  $y := \frac{\hat{y}}{\alpha}$  solves Problem 4 (Linear Complementarity Problem (LCP)).

---

This result establishes that we can use the MILP representation both to find out if the LCP problem has a solution, and to find a solution when one exists. Furthermore, by varying  $\tilde{\omega}$  we can determine which solution is returned, when there are multiple. In the limit as  $\tilde{\omega} \rightarrow 0$ , the MILP solver will return the solution which minimises  $\|q + My\|_{\infty}$ , and in the limit as  $\tilde{\omega} \rightarrow \infty$ , the MILP solver will return the solution to the LCP which minimises  $\|y\|_{\infty}$ . The former objective would ensure that the returned solution does not generate large oscillations in the path of the constrained variable, and the latter would ensure that the violations of the bound are minimised. Intermediate values of  $\tilde{\omega}$  result in a solution being returned that features balanced concern for these two extremes. In practice, we suggest choosing  $\tilde{\omega} = \omega \|q\|_{\infty}$  where  $\omega > 0$  is another constant, to ensure that the solution returned scales appropriately with  $q$ .

### 3. Higher accuracy algorithms

#### 3.1. Higher order polynomial approximations

#### 3.2. Integrating over future uncertainty

#### 3.3. Hybrid local/global approach

#### 3.4. The dynareOBC toolkit

TODO Cite YALMIP (Löfberg 2004)

TODO Cite PTest (Tsatsomeros and Li 2000)

### 4. Performance

### 5. Conclusion

TODO Suggestion that policy makers may wish to choose policy rules to ensure that solving the LCP problem is possible in polynomial time.

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## 7. Appendices

### 7.1. Proof of uniqueness of the solution to example 2.2.1 without the bound

Suppose for a contradiction that there were at least three solutions to equation (3) in  $(0,1)$  (double counting repeated roots), even for arbitrary large  $\beta \in (0,1)$ . Let  $f_1, f_2, f_3 \in (0,1)$  be the three roots. Then, by Vieta's formulas:

$$\begin{aligned} 3 &> f_1 + f_2 + f_3 = \frac{(\alpha_{\Delta y} + \sigma)\beta + \gamma + \sigma}{\beta\sigma}, \\ 3 &> f_1f_2 + f_1f_3 + f_2f_3 = \frac{(1 + \beta)\alpha_{\Delta y} + \gamma\alpha_{\pi} + \sigma}{\beta\sigma}, \\ 1 &> f_1f_2f_3 = \frac{\alpha_{\Delta y}}{\beta\sigma}, \end{aligned}$$

so:

$$\begin{aligned} (2\beta - 1)\sigma &> \beta\alpha_{\Delta y} + \gamma > \gamma > 0 \\ \beta &> \frac{1}{2}, \quad (2\beta - 1)\sigma > \gamma, \\ \beta\sigma &> \beta\alpha_{\Delta y} + \gamma + \sigma(1 - \beta), \\ 2\beta\sigma &> (1 + \beta)\alpha_{\Delta y} + \gamma\alpha_{\pi} + \sigma(1 - \beta), \\ \beta\sigma &> \alpha_{\Delta y}. \end{aligned}$$

Also, the first derivative of equation (3) must be strictly positive at  $f = 1$ , so:

$$(1 - \beta)(\alpha_{\Delta y} - \sigma) + (\alpha_{\pi} - 2)\gamma > 0.$$

Combining all of these inequalities gives the bounds:

$$\begin{aligned} 0 &< \alpha_{\Delta y} < 2\sigma - \frac{\gamma + \sigma}{\beta}, \\ 2 + \frac{(1 - \beta)(\sigma - \alpha_{\Delta y})}{\gamma} &< \alpha_{\pi} < \frac{(3\beta - 1)\sigma - (1 + \beta)\alpha_{\Delta y}}{\gamma}. \end{aligned}$$

Furthermore, if there are multiple solutions to equation (3), then the discriminant of its first derivative must be weakly positive, i.e.:

$$\left((\alpha_{\Delta y} + \sigma)\beta + \gamma + \sigma\right)^2 - 3\beta\sigma\left((1 + \beta)\alpha_{\Delta y} + \gamma\alpha_{\pi} + \sigma\right) \geq 0.$$

Therefore, we have the following bounds on  $\alpha_{\pi}$ :

$$2 + \frac{(1 - \beta)(\sigma - \alpha_{\Delta y})}{\gamma} < \alpha_{\pi} \leq \frac{\left((\alpha_{\Delta y} + \sigma)\beta + \gamma + \sigma\right)^2 - 3\beta\sigma\left((1 + \beta)\alpha_{\Delta y} + \sigma\right)}{3\beta\sigma\gamma}$$

since,

$$\begin{aligned} & \frac{(3\beta - 1)\sigma - (1 + \beta)\alpha_{\Delta y}}{\gamma} - \frac{\left((\alpha_{\Delta y} + \sigma)\beta + \gamma + \sigma\right)^2 - 3\beta\sigma\left((1 + \beta)\alpha_{\Delta y} + \sigma\right)}{3\beta\sigma\gamma} \\ &= \frac{\left((2\sigma - \alpha_{\Delta y})\beta - \gamma - \sigma\right)\left((4\sigma + \alpha_{\Delta y})\beta + \gamma + \sigma\right)}{3\beta\gamma\sigma} > 0 \end{aligned}$$

as  $\alpha_{\Delta y} < 2\sigma - \frac{\gamma + \sigma}{\beta}$ . Consequently, there exists  $\lambda, \mu, \kappa \in [0, 1]$  such that:

$$\begin{aligned} \alpha_{\pi} &= (1 - \lambda) \left[ 2 + \frac{(1 - \beta)(\sigma - \alpha_{\Delta y})}{\gamma} \right] + \lambda \left[ \frac{\left((\alpha_{\Delta y} + \sigma)\beta + \gamma + \sigma\right)^2 - 3\beta\sigma\left((1 + \beta)\alpha_{\Delta y} + \sigma\right)}{3\beta\sigma\gamma} \right], \\ \alpha_{\Delta y} &= (1 - \mu)[0] + \mu \left[ 2\sigma - \frac{\gamma + \sigma}{\beta} \right], \\ \gamma &= (1 - \kappa)[0] + \kappa[(2\beta - 1)\sigma] \end{aligned}$$

These simultaneous equations have unique solutions for  $\alpha_{\pi}$ ,  $\alpha_{\Delta y}$  and  $\gamma$  in terms of  $\lambda$ ,  $\mu$  and  $\kappa$ . Substituting these solutions into the discriminant of equation (3) gives a polynomial in  $\lambda, \mu, \kappa, \beta, \sigma$ . As such, an exact global maximum of the discriminant may be found subject to the constraints  $\lambda, \mu, \kappa \in [0, 1]$ ,  $\beta \in [\frac{1}{2}, 1]$ ,  $\sigma \in [0, \infty)$ , by using an exact compact polynomial optimisation solver, such as that in the Maple computer algebra package. Doing this gives a maximum of 0 when  $\beta \in \{\frac{1}{2}, 1\}$ ,  $\kappa = 1$  and  $\sigma = 0$ . But of course, we actually require that  $\beta \in (\frac{1}{2}, 1)$ ,  $\kappa < 1$ ,  $\sigma > 0$ . Thus, by continuity, the discriminant is strictly negative over the entire possible domain. This gives the required contradiction to our assumption of three roots to the polynomial.