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## **Tinbergen and Theil Meet Nash: Controllability in Policy Games**

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# **Tinbergen and Theil Meet Nash: Controllability in Policy Games**

## **Summary**

This paper generalizes the classical theory of economic policy to a static LQ-strategic context between  $n$  players. We show how this generalized version of controllability can profitably be used to deal with policy ineffectiveness issues and Nash equilibrium existence.

**Keywords:** Policy games, policy ineffectiveness, static controllability, Nash equilibrium existence

**JEL Classification:** C72, E52, E61

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## 1. Introduction

In the last decade or so issues of effectiveness for specific policy instruments have been raised within the context of static policy games since the pioneering articles of Stokey (1990) and Gylfason and Lindbeck (1994)<sup>1</sup> who generalize the rational expectations models *à la* Sargent and Wallace (1975) by explicitly modelling private sector strategies. In particular, explicitly or implicitly formal conditions leading to monetary policy ineffectiveness – or neutrality – have been investigated in some of the papers mentioned. Such conditions appear significantly different from those stated in the classical analysis of policy effectiveness and controllability, initially formulated by Jan Tinbergen and Henri Theil.<sup>2</sup>

We aim to show how the classical theory of economic policy can deal with policy ineffectiveness and Nash equilibrium existence issues by extending it from a single decision-maker context to a strategic multi-player one. For the sake of simplicity, we limit ourselves to the common LQ-games in a perfect information static context. Our simple logic can be extended to more complex frameworks.

## 2. The Model

We consider an economy where  $n$  players interact. We assume that each player minimizes a LQ-criterion. For reasons that will be clear later, we find it useful to distinguish between the targets that enter the criterion only linearly and the others. By assuming that player  $i$ 's criterion is defined over  $t(i) = q(i) + l(i)$  variables, where  $l(i)$  is the number of those that enter only linearly and  $q(i)$  is the number of other target variables, the LQ-criterion can be formally written as:<sup>3</sup>

$$(1) \quad U_i = \frac{1}{2} (y_i - \bar{y}_i)' Q_i (y_i - \bar{y}_i) + y_i' R_i + \tilde{y}_i' L_i \quad \forall i \in N$$

where  $N$  is the set of the  $n$  players;  $y_i \in \mathbb{R}^{q(i)}$  is a vector of target variables that enter equation (1) at least in a quadratic manner (second order);  $\bar{y}_i \in \mathbb{R}^{q(i)}$  is a vector of target

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<sup>1</sup> See the papers surveyed in Cukierman (2004) and Acocella and Di Bartolomeo (2004).

<sup>2</sup> See, among others, Preston and Pagan (1982: Chapters 1-3) and Hughes Hallett (1989).

<sup>3</sup> For reasons that we shall clarify we keep targets and instruments formally separate. However, in order to take account of the costs of some instruments, we could simply introduce additional targets into equation (1) as well as equality constraints between them and the instruments into equation (2) below.

values;  $\tilde{y}_i \in \mathbb{R}^{l(i)}$  is a vector of target variables that enter only linearly (first order);  $Q_i$  is an appropriate diagonal matrix,  $R_i$  and  $L_i$  are appropriate vectors. Note that  $Q_i$  is a full rank square matrix by assumption. We refer to  $\bar{y}_i$ ,  $Q_i$ ,  $R_i$  and  $L_i$  as the parameters of player  $i$ 's criterion. Notice that player  $i$ 's first best (or *optimum optimorum*) corresponds to its target values only if  $R_i = 0$ .

All the control vectors are sub-vectors of  $u \in \mathbb{R}^M$  and all the target variable vectors are sub-vectors of  $y \in \mathbb{R}^K$ . Each player  $i$  controls a sub-vector of  $u$ , i.e.  $u_i \in \mathbb{R}^{m(i)}$ . Of course,  $\sum_{i \in N} m(i) = M$ , since a control cannot be set by more than one player by definition. For the sake of simplicity, we also assume that each player cannot control more instruments than its targets, i.e.  $m(i) \leq t(i)$ . By contrast, players can share some target variables. Thus  $\sum_{i \in N} t(i) \geq K$ . The  $K$  target variables are linked together by the following linear equation system:

$$(2) \quad y = Au + F.$$

Each line of the above equation system represents a linear relation between one target and the instrument vector  $u$ . Vector  $F \in \mathbb{R}^K$  is a vector of given constants that are outside the players' control.<sup>4</sup> To keep things simple, we assume that the basis of  $A$  is the identity matrix, which means that system (2) cannot be reduced to many independent sub-systems.<sup>5</sup>

From equation (2), we can extract  $y_i$  and  $\tilde{y}_i$ , obtaining the relevant sub-system for player  $i$ :

$$(3) \quad \begin{bmatrix} y_i \\ \tilde{y}_i \end{bmatrix} = \begin{bmatrix} C_i \\ \tilde{C}_i \end{bmatrix} u_i + \sum_{j \in N \setminus i} \begin{bmatrix} E_{ij} \\ \tilde{E}_{ij} \end{bmatrix} u_j + F_i.$$

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<sup>4</sup> It can also contain i.i.d. shocks. In this case our results hold in expected terms by the certainty-equivalence principle.

<sup>5</sup> This assumption can be relaxed by introducing the concept of sub-controllability, which enables us to generalize our results to a larger class of policy-games (see Acocella and Di Bartolomeo, 2005). However, since the generalization adds nothing to the basic mechanism that this paper aims to illustrate, we do not consider it here.

where  $C_i \in \mathbb{R}^{q(i) \times m(i)}$ ,  $\tilde{C}_i \in \mathbb{R}^{l(i) \times m(i)}$ ,  $E_{ij} \in \mathbb{R}^{q(i) \times m(j)}$ ,  $\tilde{E}_{ij} \in \mathbb{R}^{l(i) \times m(j)}$ , and  $F_i \in \mathbb{R}^{t(i)}$  are appropriate matrices and vector.

We begin by introducing the definitions of controllability (in the Tinbergen-Theil's fashion<sup>6</sup>) and policy ineffectiveness.

**Definition (Q-controllability):** *Player  $i$  can Q-control system (3) if the number of its instruments equals the number of its quadratic targets:  $m(i) = q(i)$ . If policy-maker  $i$  can Q-control its system,  $y_i \in \mathbb{R}^{q(i)}$  is its controllable set.*

The above definition implies that in the static single-player case ( $n = 1$ ), the decision-maker is able to obtain its first best. In fact, if  $m(i) = t(i) > q(i)$ , a finite solution for the problem does not exist.<sup>7</sup> It is worth noticing that Q-controllability implies that  $C_i$  is a square matrix.

**Definition (ineffectiveness):** *Player  $i$ 's policy is ineffective with respect to one (or more of its) target variable(s) if the equilibrium value of that (those) variable(s) is never affected by changes in the parameters of the player's criterion.<sup>8</sup>*

The Nash equilibrium can be decoupled in a set of  $n$  traditional Tinbergen-Theil problems (i.e. minimizing equation (1) subject to (3) for each of the  $n$  players), which is the set of the reaction correspondences. With reference to this decoupled representation of the policy game, we can state the following theorem.

**Theorem 1 (existence):** *The Nash equilibrium of the policy game described does not exist if and only if (a) for at least one player:  $L_i \neq 0$  and  $t(i) = m(i)$ ; or (b) the intersection of players' controllable sets is not empty.*

Proof. The optimization problem of each player implies the following  $n$  focs:

$$(4) \quad \frac{\partial U_i}{\partial u_i} = C'_i Q_i C_i u_i + C'_i Q_i \sum_{j \in N/i} E_{ij} u_j + C'_i (R_i + L_i - Q_i \bar{y}_i + Q_i F_i) = 0 \quad \forall i \in N.$$

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<sup>6</sup> Our definition slightly differs from that used in the traditional theory of economic policy because it is instrumental to our aim. However, notice that the traditional case is a particular case of our definition (i.e.  $t(i) = q(i)$ ). See Preston and Pagan (1982: Chapters 1-3).

<sup>7</sup> The first best implies infinite values of the variables that enter the criterion linearly.

<sup>8</sup> In a strategic context policies are endogenous. Thus ineffectiveness must be formulated in endogenous terms too.

Now, let us consider the case of player 1 without loss of generality and assume that  $m(1) = t(1) > q(1)$  and that a solution  $(u_1^*, u_j^*)$  exists—where  $u_j^*$  represents the controls of all the players other than player one. If  $(u_1^*, u_j^*)$  is the solution, given  $u_j^*$ ,  $u_1^*$  must satisfy the first order condition (4) for player 1, but no finite value of  $u_1$  could, since  $\det(C_1'Q_1C_1) = 0$  (thus, cannot be inverted) if  $m(1) = t(1) > q(1)$ .<sup>9</sup>

Let us consider the second part of the theorem focusing on the first two players without any loss of generality. Assume that they share all their variables and Q-control their sub-systems and assume that a solution  $(u_1^*, u_2^*, u_j^*)$  exists. Then given  $u_j^*$ ,  $(u_1^*, u_2^*)$  must satisfy the system of first-order conditions of the first two players, i.e.:

$$(5) \quad \begin{bmatrix} C_1'Q_1C_1 & C_1'Q_1E_{12} \\ C_2'Q_2E_{21} & C_2'Q_2C_2 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} C_1'Q_1 \sum_{j \in N \setminus \{1,2\}} E_{1j}u_j^* + C_1'(R_1 + L_1 - Q_1\bar{y}_1 + Q_1F_1) \\ C_2'Q_2 \sum_{j \in N \setminus \{1,2\}} E_{2j}u_j^* + C_2'(R_2 + L_2 - Q_2\bar{y}_2 + Q_2F_2) \end{bmatrix}$$

However, the first matrix of (5) cannot be inverted since, according to our assumptions,  $C_1 = E_{21}$  and  $C_2 = E_{12}$ . Hence no  $(u_1^*, u_2^*)$  can satisfy (5) and  $(u_1^*, u_2^*, u_j^*)$  cannot be the solution. Finally, consider the case where the first two players do not share all their targets. It can be simply solved by considering the problem of each player as two independent problems: a) minimize linear-quadratic deviations from shared targets plus all first-order targets with respect to an arbitrary set of instruments of a number equal to the quadratic variables; b) minimize linear-quadratic deviations from non-shared targets plus all first-order targets with respect to the other instruments (which equal the targets because of the Q-controllability).<sup>10</sup> As above, now the impossibility of a solution emerges for the first-order condition of the problems a). Summarizing, as claimed, if at

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<sup>9</sup> In such a case,  $Q_1$  equals  $T_1 T_1'$  where  $T_1 = \left[ \sqrt{Q_1} : \emptyset \right] \in \mathbb{R}^{q(1) \times t(1)}$ , i.e.  $T_1$  is obtained in two steps: first by considering a  $q(1) \times q(1)$  matrix with the square roots of each element  $Q_1$  and then by adding  $t(1)$  columns of zeros. Thus  $\det(C_1'Q_1C_1) = \det(C_1'T_1)\det(T_1'C_1)$  equals zero since it is easy to verify that all the elements of the last  $t(1)$  columns of  $C_1'T_1$  are zeros.

<sup>10</sup> Notice that because of the controllability the result is independent of the assignment of the instruments.

least two players Q-control their sub-systems and share at least one target variable (and thus the player controllable set is not empty), the Nash equilibrium does not exist. ■

In an unusual way, we have derived the necessary and sufficient condition for the existence of the Nash equilibrium in terms of a counting rule of the number of instruments and targets. It is then useful to compare our results with a well-known theorem of the existence of Nash equilibrium.

In an LQ-context, a sufficient condition for the Nash equilibrium existence<sup>11</sup> is that the space of strategies of each player is convex and compact. If players' controls are unbounded, the Nash equilibrium may not exist. The introduction of quadratic instrument costs<sup>12</sup> would make them bounded, thus assuring the existence of equilibrium. In our terms, this would imply that the dimensions of matrices  $Q_i$  become  $t(i) + m(i)$ . Thus, the number of instruments would always be less than the number of targets, the system would not be Q-controllable by any player and equilibrium would exist. Note, however, that Theorem 1 is more general than the theorem of existence, mentioned since that of instrument costs is a particular case.

Once the Nash equilibrium is decoupled into a set of  $n$  traditional Tinbergen-Theil problems, provided that equilibrium exists, player  $i$ 's policy is ineffective with respect to the targets shared with the players who perfectly Q-control their sub-systems. A straightforward condition for policy ineffectiveness can thus be defined as follows.

**Theorem 2 (ineffectiveness):** *Player  $i$ 's policy is ineffective for all the target variables contained in the complement of the intersection between its controllable set and the union of all players' controllable sets.*

Proof. Foc in terms of quasi-reaction functions are:

$$(6) \quad \frac{\partial U}{\partial u_i} = C_i' Q_i (y_i - \bar{y}_i) + C_i' R_i + \tilde{C}_i' L_i = 0 \quad \forall i \in N$$

Equations (6) represent the optimal value of the target variables that assure the minimization of player  $i$ 's criterion, given the policy of the others. Thus, by definition, all the conditions (6) have to be mutually verified to ensure the Nash equilibrium.

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<sup>11</sup> See e.g. Dasgupta and Maskin (1986).

<sup>12</sup> See footnote 3.

Formally, equations (6) map the vector of target variables into that of the desired target values.<sup>13</sup> If player  $i$  can Q-control its sub-system, then condition (6) becomes:

$$(7) \quad y_i = \bar{y}_i - Q_i^{-1} R_i - \left( C_i' Q_i \right)^{-1} \tilde{C}_i' L_i$$

If the Nash equilibrium exists, it is unique, because of the LQ-structure considered. Hence, if the equilibrium exists and player  $i$  can Q-control its sub-system, the Nash equilibrium will satisfy equation (7) and any other player will not be able to affect the value of any of the variables in  $y_i$ , i.e. those in the controllable set of player  $i$ . ■

Finally, we should note that neutrality (for the players different from  $i$ ) associated with  $l(i) \neq 0$  differs from that emerging in the case of  $l(i) = 0$ . The former is somewhat weaker than the latter. In fact, if  $l(i) = 0$  player  $i$  is the only one that can influence its targets and it always achieves its first best. By contrast, if  $l(i) \neq 0$ , despite the fact that only player  $i$  can influence its targets, it does not achieve its first best and can thus improve its position, e.g. by using the first mover advantage in Stackelberg games or by cooperating.<sup>14</sup>

### 3. Conclusions

In this paper we have first generalized the conditions for policy controllability from a parametric context to a strategic multi-player one. Once static controllability has been reinterpreted to suit the strategic nature of the setting, policy ineffectiveness merely becomes an instrument/target accounting problem in the traditional Tinbergen-Theil's vein. In a game theoretical perspective, controllability and ineffectiveness are in fact dual concepts: controllability of the system for one player implies that other players' strategies (instruments) are ineffective. A problem of existence of the Nash equilibrium can arise, when more than one player sharing at least a common target apparently control the system and their controls are unbounded.

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<sup>13</sup> It is worth noticing that for each player condition (6) represents the dual problem of that described by equation (4). If the reaction function system (4) is over-determined, the quasi-reaction function system is under-determined; and vice versa.

<sup>14</sup> See Acocella and Di Bartolomeo (2004 and 2005) for some examples.

The simple logic of our discussion can be extended to more complex contexts such as dynamic and non-linear ones. However, formal generalizations may face computational and practical problems.

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(lxv) This paper was presented at the EuroConference on "Auctions and Market Design: Theory, Evidence and Applications" organised by Fondazione Eni Enrico Mattei and sponsored by the EU, Milan, September 25-27, 2003

(lxvi) This paper has been presented at the 4<sup>th</sup> BioEcon Workshop on "Economic Analysis of Policies for Biodiversity Conservation" organised on behalf of the BIOECON Network by Fondazione Eni Enrico Mattei, Venice International University (VIU) and University College London (UCL) , Venice, August 28-29, 2003

(lxvii) This paper has been presented at the international conference on "Tourism and Sustainable Economic Development – Macro and Micro Economic Issues" jointly organised by CRENOS (Università di Cagliari e Sassari, Italy) and Fondazione Eni Enrico Mattei, and supported by the World Bank, Sardinia, September 19-20, 2003

(lxviii) This paper was presented at the ENGIME Workshop on "Governance and Policies in Multicultural Cities", Rome, June 5-6, 2003

(lxix) This paper was presented at the Fourth EEP Plenary Workshop and EEP Conference "The Future of Climate Policy", Cagliari, Italy, 27-28 March 2003

(lxx) This paper was presented at the 9<sup>th</sup> Coalition Theory Workshop on "Collective Decisions and Institutional Design" organised by the Universitat Autònoma de Barcelona and held in Barcelona, Spain, January 30-31, 2004

(lxxi) This paper was presented at the EuroConference on "Auctions and Market Design: Theory, Evidence and Applications", organised by Fondazione Eni Enrico Mattei and Consip and sponsored by the EU, Rome, September 23-25, 2004

(lxxii) This paper was presented at the 10<sup>th</sup> Coalition Theory Network Workshop held in Paris, France on 28-29 January 2005 and organised by EUREQua.

(lxxiii) This paper was presented at the 2nd Workshop on "Inclusive Wealth and Accounting Prices" held in Trieste, Italy on 13-15 April 2005 and organised by the Ecological and Environmental Economics - EEE Programme, a joint three-year programme of ICTP - The Abdus Salam International Centre for Theoretical Physics, FEEM - Fondazione Eni Enrico Mattei, and The Beijer International Institute of Ecological Economics

(lxxiv) This paper was presented at the ENGIME Workshop on "Trust and social capital in multicultural cities" Athens, January 19-20, 2004

(lxxv) This paper was presented at the ENGIME Workshop on "Diversity as a source of growth" Rome November 18-19, 2004

(lxxvi) This paper was presented at the 3rd Workshop on Spatial-Dynamic Models of Economics and Ecosystems held in Trieste on 11-13 April 2005 and organised by the Ecological and Environmental Economics - EEE Programme, a joint three-year programme of ICTP - The Abdus Salam International Centre for Theoretical Physics, FEEM - Fondazione Eni Enrico Mattei, and The Beijer International Institute of Ecological Economics

(lxxvii) This paper was presented at the Workshop on Infectious Diseases: Ecological and Economic Approaches held in Trieste on 13-15 April 2005 and organised by the Ecological and Environmental Economics - EEE Programme, a joint three-year programme of ICTP - The Abdus Salam International Centre for Theoretical Physics, FEEM - Fondazione Eni Enrico Mattei, and The Beijer International Institute of Ecological Economics.

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