EUROPEAN UNIVERSITY INSTITUTE, FLORENCE
DEPARTMENT OF ECONOMICS

EUI WORKING PAPER No. 85/158

ON THE DETERMINATION OF MACROCECONOMIC POLICIES WITH ROBUST OUTCOME

by

Christophe Deissenberg

A preliminary version of this article appears under the title "Robustifying macroeconomic policies" in: G. Feichtinger (ed.): <u>Economic Applications of Optimal Control II</u>, North Holland 1985. Most sincere thanks are due to K.V. for his very motivating critique of the approach followed here.

BADIA FIESOLANA, SAN DOMENICO (FI)

Printed in Italy in April 1985
European University Institute
Badia Fiesolana
50016 San Domenico (Fi)
Italy

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Christophe Deissenberg
Universität Konstanz, FRG
and
European University Institute, Florence, Italy

With particular regard to applications in macroeconometric policy-making, an optimization framework is presented for both continuous- and discrete-time systems which injects an element of robustness into the optimal solution: The dynamic behaviour of selected variables is rendered less sensitive to variations of the system's parameters by taking into consideration appropriate sensitivity vectors in an augmented objective function. The approach's potential usefulness is explored with a small econometric model for Germany.

INTRODUCTION

In spite of the heavy criticism it has been subjected to, the minimization of a welfare loss function subject to an econometric model of the economy considered still provides a priviledged framework for macroeconomic policy discussions. Within this framework, thr uncertainty about the true dynamics of the economy - econometric models are, after all, only very imperfect descriptions of the reality- has usually be treated in a probabilistic manner by minimizing the expected value of the loss function under estimated or postulated distributions of the model's parameters and residuals, see e.g. Chow (1975), (1981), Kendrick (1981). One potential weakness of this way of treating uncertainty is that, by definition, it is aimed at determining policies insuring good <u>average</u> results over <u>all possible</u> realizations of the uncertain parameters and variables. These policies, however, are not specifically designed to perform well or even acceptably in the unique historical situation in which they will be used (i.e., they do not insure good results for <u>every</u>

specific realization of the uncertain values).

In practical macroeconomic policy-making, on the other hand, concern does not usually centre on the average economic performance over a set of possible evolutions, but on the results actually obtained in the periods considered. Thus, there is a natural interest in policies which not only insure a small expected welfare loss but also a high insensitivity of the actual economic performance to some type of uncertainty.

In this paper, we assume that the econometric model used in economic policy determination correctly reflects the structure of the economy. However, the estimated values of the model's parameters differ in an unknown manner from their true values: That is, we assume parameter disturbances. For increased generality, the parameter disturbances are taken to depend on a vector of variables of unknown value. We are interested in policies which - while insuring a satisfactory expected economic performance - protect us from parameter disturbances in the following way : they should insure that the realized and the predicted trajectories of the variables of interest remain for arbitrary small disturbances closer to eachother than would be the case if one followed the standard "optimal" policies mentioned above. In other words, the policies considered should reduce the"trajectory sensitivity" of the controlled economy to small parameter variations.

The approach presented here has its roots in parametric sensitivity methods well known to engineers, see Frank (1978) for an overview, but largely ignored in the economic literature. An exception is the paper by Karakitsos, Rustem and Zarrop (1980). While similar to ours in its general philosophy, the approach proposed by these authors nevertheless presents an important difference: It aims at insuring a relative insensitivity of the optimal value of the objective function, and not of the optimal trajectory. In a related vein, Mitchell (1979) and Stöppler (1979) consider within the linear-quadratic-gaussian framework the problem of reducing the variance/

covariance of the expected optimal trajectory. Other authors have approached the problem of robust economic policies from the point of view of worst case policies, minimal guaranteed welfare, etc. Since the alternative approaches proposed are very numerous and formally unrelated to the one presented here, they are not referred to in this article.

The paper is organized as follows. The next section is devoted to the presentation of the formal sensitivity reduction problem. Motivated by the growing interest in continuous-time econometric models, see Gandolfo (1981), we first discuss the general case of a dynamic structure represented by a system of non-linear differential equations. We then turn to the discrete-time linear-quadratic case, the bread and butter of macroeconometric policy optimization. To increase the clarity of the presentation, we disregard here the stochastic elements such as additive disturbances which are characteristic for econometric models. Nonetheless it should be clear that the "deterministic treatment of uncertainty" advocated in this paper cannot pretend to supplant the traditional probabilistic approach; possibly it may complement it. Our implicit concern with stochastic elements explains in particular the emphasis placed in the paper on closed-loop policies.

In the paper's final part we present an application of the sensitivity reduction method to a small econometric model for the Federal Republic of Germany. The numerical analysis gives insights into the relative importance of different model parameters for the trajectory sensitivity, into the trade-offs between economic performance and sensitivity, into the maximally attainable sensitivity reduction and into the way the control efforts vary with increased sensitivity reduction. It should be noted that very little numerical evidence on the signification of sensitivity reduction in macroeconometric policy-making has yet been published, an exception being the articles by Stöppler and by Karakitsos et al. mentioned earlier.

THE FORMAL PROBLEM AND ITS SOLUTION

The general continuous-time case

Consider the following situation: A real system with unknown dynamics

(1a) $$\dot{x}^r_t = f^r(x^r_t, u_t, t) =$$

$$= f(x^r_t, u_t, t, \alpha)\big|_{\alpha=\alpha^r}, \quad t\varepsilon\left[0, T\right],$$

(1b) x^r_o = a given,

is modelled by the estimated system

(2a) $$\dot{x}^n_t = f^n(x^n_t, u_t, t) =$$

$$= f(x^n_t, u_t, t, \alpha)\big|_{\alpha=\alpha^n}, \quad t\varepsilon\left[0, T\right],$$

(2b) x^n_o = a given,

where for every $t\varepsilon\left[0, T\right]$

x_t is a nxl state vector,

u_t is a mxl control vector,

α^n is the estimated value of a scalar time-independent parameter α whose true value α^r is unknown.

The only difference between the true system (1) and the estimated system (2) lies in the value of the parameters α. The future values x^n_t, $t>0$, are to be understood as forecasted values, based on the knowledge of the estimated model and on the known values (true=estimated) of the current state x_o. The state x_t incorporates all relevant information on the system's history up to $t\geq 0$.

The solution $\{x^r_t\}$ of (1) will be called the actual or real state trajectory, the solution $\{x^n_t\}$ of (2) the predicted trajectory. These solutions are assumed to exist, to be unique, bounded, and continuous in α and t for all admissible values of α and $\{u_t\}$. The condition insuring that these assumptions are fulfilled are standard and shall not be elaborated upon here.

Note that we do not distinguish between real and predicted controls. That is, we assume that the controls are always physically realized as planned. This assumption, however, can easily be relaxed. Moreover, it does not preclude the possibility that for some or all t the controls u_t are determined as functions of (perfect or imperfect) observations of the real state trajectory up to t. That is, feedback control is acceptable. Note that we assume for simplicity's sake that perfect observations of the current real state are available in each period.

The discrepancy

$$(3) \qquad \Delta\alpha := \alpha^r - \alpha^n$$

between the known estimated value α^n of α and its unknown true value α^r will be called parameter disturbance. Let Δx_t designate the state disturbance in t resulting from the parameter disturbance $\Delta\alpha$:

$$(4) \qquad \Delta x_t := x_t^r - x_t^n \quad , \qquad t\varepsilon \left[0, T\right] \; .$$

Note that the model disturbances $\Delta\alpha$ and Δx_t are functions of the true values and thus unknown.

Since x_t^n and x_t^r are continuous in α, the disturbance Δx_t is also continuous in α. We shall further assume that it can be expressed trough Taylor expansion of f around its estimated value as:

$$(5) \qquad \Delta x_t = \frac{\partial x_t^n}{\partial \alpha} \cdot \Delta\alpha + \frac{1}{2} \frac{\partial^2 x_t^n}{\partial \alpha^2} \cdot (\Delta\alpha)^2 + \dots \; ,$$

where all the derivatives are evaluated at $\alpha=\alpha^n$.

For sufficiently small parameter disturbances $\Delta\alpha$, one may neglect without prejudice the terms of order 2 or higher in (5), obtaining as approximation for Δx_t the linear expression

(6) $\Delta x_t \approx \psi_t \cdot \Delta\alpha \;, \quad t \varepsilon \left[0,\; T\right] \;,$

where $\psi_t := \partial x_t^n / \partial\alpha_{|\alpha = \alpha^n}$ is the n x 1 sensitivity vector for period t.

The class of disturbances $\Delta\alpha$ for which the approximation of (5) by (6) is acceptable must, of course, be determined in the context of each concrete case.

To the first order, ψ_t governs the state disturbance Δx_t resulting from a parameter disturbance $\Delta\alpha$. Specifically, its i-th coordinate expresses the sensitivity of the i-th state variable in t with respect to a marginal pertubation of α.

It is important for us that ψ_t depends only on estimated values and thus can be computed, even though the true system is unknown. Specifically, ψ_t can be obtained for all t's as the solution of the differential equation obtained by differentiating (2) with respect to α. (Under the assumptions made, this solution exists, is unique and continuous). We shall distinguish two cases according to whether the controls u_t depend on α^r or not:

Case I : $\partial u_t / \partial\alpha = 0$ for all t. That is, $\{u_t\}$ does not depend on the real state trajectory $\{x_t^r\}$: the controls u_t are determined open-loop for all t. In that case we designate ψ_t by ρ_t and call it open-loop sensitivity. One has

(7a) $$\dot{\rho}_t = \frac{\partial f^n}{\partial x_t} \rho_t + \frac{\partial f^n}{\partial\alpha} \;, \quad t \varepsilon \left[0,\; T\right]$$

(7b) $$\rho_o = 0.$$

Case II : $\partial u_t / \partial\alpha \neq 0$ for some t. This is always the case when u_t is determined as a function of (some measurement of) $\{x_t^r\}$. In this case, ψ_t will be called closed-loop sensitivity and denoted by σ_t. One obtains

(8a) $\dot{\sigma}_t = \left(\frac{\partial f^n}{\partial x_t} + \frac{\partial f^n}{\partial u_t}\frac{\partial u_t}{\partial x_t}\right)\sigma_t + \frac{\partial f^n}{\partial \alpha} + \frac{\partial f^n}{\partial u_t}\frac{\partial u_t}{\partial \alpha} \; , \quad t\varepsilon\left[0,\, T\right]$,

(8b) $\sigma_0 = 0$.

In (7) and (8), all derivatives are taken at $\alpha = \alpha^n$.

Equation (7) is of course a trivial special case of (8). The reason for distinguishing ρ_t and σ_t will become apparent at a later point. Whenever this distinction is not essential, we shall keep using the symbol ψ_t to designate either open-loop or closed-loop sensitivity.

Equation (7) resp. (8) defines a (linear) sensitivity model which parallels the (linear or non-linear) process model (2). Indeed the sensitivity model is of the same order and of the same dimension as the original model.

The sensitivity model is ignored in economic optimization problems as usually formulated: The "classical economic optimization problem" or primary problem P can broadly be characterized as follows:

(P) Using the estimated model (2) as a constraint, find a strategy which minimizes a welfare loss function

$$J^P = \int_0^T j^P(x_t^n,\, u_t,\, t)\,dt.$$

The function J^P expresses the economic or social costs of following a given control strategy.

Two things are to be noted here: The loss function J^P is

a) a function of the estimated values of the economic variables; but not

b) of the state disturbances Δx_t. These disturbances do not play any role in the optimization calculation, either directly or indirectly.

Of course, this does not mean that there are no sensitivity considerations in theoretical or applied economic analysis. What we are suggesting here is that in the macroeconometric policy-making context sensitivity considerations should be integrated into the formal optimization problem from the outset and not treated as an ex post test of how robust solutions are.

Consider now the problem of finding a control strategy such that the resulting real trajectory remains in some sense as close as possible to the predicted one; this, for arbitrary small parameter disturbances $\Delta\alpha$. In this problem $\{x_t^n\}$ is no longer of importance. The state perturbations $\{\Delta x_t\}$ are now the object of the control.

However, since Δx_t is a function of the unknown parameter disturbance $\Delta\alpha$, it is not possible to control Δx_t directly. One may control it indirectly, though, by minimizing a suitable norm of the sensitivity vector ψ_t. Thus the pure <u>sensitivity reduction problem</u> may be expressed in fairly general terms as

(S) Using the estimated model (7) (open-loop case) or (8) (closed-loop case) as constraint, find a control strategy which minimizes an appropriate function $J^S = \int_0^T j^S(\psi_t, u_t, t)dt$.

Assuming now that the decision-maker is interested in a compromise between pure predicted performance maximization in the sense of P on the one hand, and pure trajectory sensitivity reduction in the sense of S on the other, we consider in this paper a <u>combined problem</u> C

$$(C)\quad \begin{cases} J = J^P + \lambda J^S \rightarrow \min\ , \ \lambda \geq 0 \\ \text{subject to (2) and (7) or (8).} \end{cases}$$

The weight λ expresses the relative importance given to sensitivity reduction, with the two polar cases $\lambda = 0$ (corresponding to the primary problem) and $\lambda = \infty$ (i.e., pure sensitivity reduction). Note that in general J^P and J^S will be concurring objectives; it is by no means certain that, in a given problem, a significant reduction in sensitivity can be achieved without unacceptable loss in primary performance.

In the open-loop case, the combined problem C is standard and does not need to be further elaborated upon. On the other hand, problems do arise in the closed-loop case. The proper sensitivity vector in that case, σ_t, depends on the control strategy used. Thus the optimal feedback rule as a result of the optimization is needed in the problem formulation in order to properly define σ_t. In some cases it will be possible to solve this problem by approximating σ_t by ρ_t in the closed-loop sensitivity problem. However, σ_t may be so different from ρ_t that the addition of terms involving ρ_t in the combined performance index J may be detrimental rather than beneficial; see Kreindler (1968). One will then have to resort to more or less elaborate numerical solution procedures, depending on the specific class of problems studied.

Remarks:

i) For simplicity's sake we considered only the case of a scalar parameter α. When α is a kx1 vector, one may derive k sensitivity models in the format (7) or (8)--each one of these models being associated to one coordinate of α--and take into consideration the k corresponding nx1 sensitivity vectors in J^S. Alternatively, instead of the k partial derivatives $\partial x_t^n / \partial \alpha_i$, one may use a single directional derivative $\delta x_t^n / \delta \alpha$ in a given direction $\delta \alpha$. The problem then is equivalent to the scalar one. We follow this last approach in the numerical part. When J^S is restricted to the (fairly general) form $J^S = \sum_{it}\sum \gamma_{it} \left\| \partial x_t^n / \partial \alpha_i \right\|$, the two approaches are basically equivalent, the problem of determining appropriate weights γ_{it} for the k sensitivity vectors $\partial x_t^n / \partial \alpha_i$ in the first case corresponding to the problem of finding proper directions $\delta \alpha_{it}$ in the second. Of course, the basic problem of finding a weighting scheme (a direction) reflecting in a satisfactory way the preferences of the decision-maker (or more pragmatically: leading to sensible solutions) may be extremly harduous to solve in practice.

ii) The approach can be immediately extended to cover a) the case of (slowly) time-varying parameters α; and b) the case of disturbances Δx_o in the initial state. See Frank (1978), Turetscheck (1979) for details.

iii) A formal requirement for a senseful application of the sensitivity reduction method is: The underlying model must be structurally stable. Loosely speaking, a dynamic system is structurally stable when small perturbations of its parameters do not essentially modify its qualitative behaviour. See Varian (1981), pp. 107-107, for a more formal definition of the concept and for further references. The point will not be pursued here. Note, however, that it is reasonable to expect from any econometric model that it is structurally stable. Furthermore, it is generally possible to cope with structural instability through simple extension of the original model, see Frank (1978).

iv) Since we are working in the time domain, the sensitivity expressions used here do depend on the values taken by the exogenously determined variables. To obtain results which depends exclusively on the system's structure one has to work in the frequency domain. In this context we will like to mentionned here the corresponding work on pole placement conducted by the Cambridge Control Group around McFarlane.

The discrete-time linear-quadratic case

The primary problem. The primary linear-quadratic problem PLQ considered in the numerical part of the paper is given by

(PLQ)

$$(9)\quad J^P = \sum_{t=1}^{T} \frac{1}{2}(x_t - \bar{x}_t)'K^P(x_t - \bar{x}_t) \to \min_{u_1, \ldots, u_T}$$

subject to the linear econometric model in state variable form

$$(10a)\quad x_t = A^P x_{t-1} + B^P u_t + C^P z_t \ ,$$

$$(10b)\quad x_o = \text{a given},$$

where

"'" denotes transposition,

x_t and u_t are the nxl predicted state vector and the mx1 control vector,

$\bar{x}_t$ is a given vector of desired values for x_t,

z_t is a qxl vector of given exogenous variables,

K^P is a given nxn symmetric positive semi-definite matrix,

A^P, B^P and C^P are given estimated coefficient matrices of appropriate dimensions.

The matrices A^P, B^P and C^P may depend on time.

All values in (9)-(10) are estimated (predicted). To simplify the notation, however, we do not use the superscript "n". Furthermore, we assume without loss of generality, following Chow (1975), that u_t is included in x_t as a subvector. That is, x_t has the form $x_t = (\hat{x}_t', u_t')'$.

Linear-quadratic control problems of the type (9)-(10) play a central role in connection with the optimal control of macroeconomic models for analysis and policy determination purposes; see again Chow (1975), (1981). The optimal solution of PLQ can be expressed in the form of a linear feedback of the current state,

$$(11)\quad u_t^* = G_t^P\, x_{t-1} + g_t^P \ , \quad t = 1, \ldots, T \ .$$

Here and in the following a star * denotes an optimal value.

<u>The sensitivity equations</u>. We assume that the coefficient matrices in (10) are continuous functions of a time invariant parameter α,

their estimated values A^P, B^P and C^P corresponding to $\alpha = \alpha^n$. In complete analogy to the continuous-time case, one can then derive a linear first-order difference equation for $\partial x_t / \partial \alpha =: \Psi_t$, $t = 1, \ldots, T$. Differentiating (10) with respect to α, one obtains in the open-loop case

$$\text{(12a)} \quad \frac{\partial x_t}{\partial \alpha} = \rho_t = \frac{\partial A^P}{\partial \alpha} x_{t-1} + A^P \rho_{t-1} + \frac{\partial B^P}{\partial \alpha} u_t + \frac{\partial C^P}{\partial \alpha} z_t \ , \ t = 1, \ldots, T \ ,$$

$$\text{(12b)} \quad \frac{\partial x_o}{\partial \alpha} = \rho_o = 0 \ .$$

Here, and in the following, all derivatives are taken at the estimated values.

In the case of a linear feedback of the form (11), substituting (11) for u_t in (10) and differentiating the resulting expression with respect to α yields for the closed-loop sensitivity σ

$$\text{(13a)} \quad \frac{\partial x_t}{\partial \alpha} = \sigma_t = \left(\frac{\partial A^P}{\partial \alpha} + \frac{\partial B^P}{\partial \alpha} G_t^P\right) x_{t-1} + (A^P + B^P G_t^P)\sigma_{t-1} + \frac{\partial B^P}{\partial \alpha} g_t^P + \frac{\partial C^P}{\partial \alpha} z_t \ , \quad t = 1, \ldots, T \ ,$$

$$\text{(13b)} \quad \frac{\partial x_o}{\partial \alpha} = \sigma_o = 0 \ .$$

<u>The sensitivity problem</u>. We assume that the criterion J^S to be minimized in the sensitivity problem is of the same type as J^P, i.e. quadratic in the sensitivity terms, both because the quadratic norm is in most cases as good a measure for trajectory sensitivity as any and for computational simplicity. The trajectory sensitivity reduction problem is accordingly given by

$$\text{(SLQ)} \quad \left| \begin{array}{l} \text{(14)} \quad J^S = \sum_{t=1}^{T} \frac{1}{2} \Psi_t' K^S \Psi_t \to \min \\ \text{subject to the appropriate equation of motion for } \Psi_t, \\ \text{i.e., to (12) or (13).} \end{array} \right.$$

One easily recognizes that the optimal solution of SLQ also minimizes $\sum_{t=1}^{T} \frac{1}{2}(\Delta\alpha)^2 \Psi_t' K^S \Psi_t$, where this last expression approximates for small $\Delta\alpha$'s the expression $\sum_{t=1}^{T} \frac{1}{2}(\Delta x_t)' K^S (\Delta x_t)$. That is, SLQ is an adequate formulation for the problem of finding a control strategy which "minimizes Δx_t" for small parameter disturbances $\Delta\alpha$.

<ins>The combined problem</ins>. In the open-loop case, one obtains immediately for the combined problem CLQ^{OL}

$$(CLQ^{OL}) \quad \left| \begin{array}{ll} (15) & J = J^P + \lambda J^S = \sum_{t=1}^{T} \frac{1}{2} (x_t-\bar{x}_t)' K^P (x_t-\bar{x}_t) + \rho_t' \lambda K^S \rho_t = \\ & \qquad = \sum_{t=1}^{T} \frac{1}{2}(y_t-\bar{y}_t)' K (y_t-\bar{y}_t) \\ & \text{subject to} \\ (16a) & y_t = Ay_{t-1} + Bu_t + Cz_t \ , \ t = 1, \ldots, T \ , \\ (16b) & y_o = \bar{a} \ , \end{array} \right.$$

where

$$y_t = \begin{pmatrix} x_t \\ \hline \rho_t \end{pmatrix} , \quad \bar{a} = \begin{pmatrix} a \\ \hline o \end{pmatrix} , \quad \bar{y}_t = \begin{pmatrix} \bar{x}_t \\ \hline o \end{pmatrix} ,$$

$$K = \left(\begin{array}{c|c} K^P & 0 \\ \hline 0 & \lambda K^S \end{array}\right) , \quad A = \left(\begin{array}{c|c} A^P & 0 \\ \hline \frac{\partial A^P}{\partial \alpha} & A^P \end{array}\right) ,$$

$$B = \begin{pmatrix} B^P \\ \hline \frac{\partial B^P}{\partial \alpha} \end{pmatrix} , \quad C = \begin{pmatrix} C^P \\ \hline \frac{\partial C^P}{\partial \alpha} \end{pmatrix} .$$

The optimal solution of CLQ^{OL} has the form

$$(17) \qquad u_t^* = G_t y_{t-1} + g_t = G_t^1 x_{t-1} + G_t^2 \rho_{t-1} + g_t \ .$$

Using (17) to control the real dynamic system by feedback, however, may not lead to the desired sensitivity reduction since in that case the trajectory sensitivity is no longer given by ρ_t, but by

$$(18a) \qquad \sigma_t = (\frac{\partial A^P}{\partial \alpha} + \frac{\partial B^P}{\partial \alpha} G_t^1) x_{t-1} + (A^P + B^P G_t^1) \sigma_{t-1} + \frac{\partial B^P}{\partial \alpha} G_t^2 \rho_{t-1}$$
$$+ B^P G_t^2 \frac{\partial \rho_{t-1}}{\partial \alpha} + \frac{\partial B^P}{\partial \alpha} g_t + \frac{\partial C^P}{\partial \alpha} z_t \ , \quad t = 1, \ldots, T \ .$$

(18b) $\sigma_o = 0$,

which is obtained by using (17) to substitute for u_t in (16) and differentiating the resulting expression with respect to α. On the other hand, it is impossible to formulate the "correct" closed-loop combined problem directly, since this requires knowledge of the optimal solution of this problem.

In order to stay in the linear-quadratic framework (a strong incentive for doing so being the widespread use of the corresponding algorithms in macroeconometric policy optimization), we do not try in the numerical part to derive an exact solution to the closed-loop combined problem. We use instead the following simple iterative procedure suggested by Kreindler (1968): At each iteration k one solves the open-loop problem CLQ^{OL} with A replaced in period t by

$$(19)\qquad A_t(k) = \left(\begin{array}{c:c} A^P & 0 \\ \hdashline \frac{\partial A^P}{\partial\alpha} + \frac{\partial B^P}{\partial\alpha}G_t^1(k-1) & A^P + B^P G_t^1(k-1) + \frac{\partial B^P}{\partial\alpha}G_t^2(k-1) \end{array}\right) ,$$

where $G_t^1(k-1)$, $G_t^2(k-1)$ are the optimal feedback matrices determined at iteration k-1. In other words, one approximates σ_t by

$$(20)\qquad \rho_t = \left[\frac{\partial A^P}{\partial\alpha} + \frac{\partial B^P}{\partial\alpha}G_t^1(k-1)\right] x_{t-1} + $$
$$+ \left[A^P + B^P G_t^1(k-1) + \frac{\partial B^P}{\partial\alpha}G_t^2(k-1)\right]\rho_{t-1} + \frac{\partial B^P}{\partial\alpha}g_t + \frac{\partial C^P}{\partial\alpha}z_t ,$$

thus indirectly insuring closed-loop sensitivity reduction. This procedure worked satisfactorily in the problems we now present.

A NUMERICAL APPLICATION

The econometric model and the primary problem

In this section we present some numerical results obtained by applying the approach outlined above to a small linear econometric model for Germany, the Uebe model. This model is discussed in detail in Stöppler and Deissenberg (1977), where it is used in diverse optimal control experiments: The "primary problem" of our sensitivity reduction exercise corresponds to "Run 1" in this previous article. It is also a slightly simplified version of the model which underlies the numerical part of the Stöppler (1979) paper on covariance reduction mentioned in the introduction. We refer to these earlier papers for specifics on the structure and properties of the Uebe model and for a complete description of the primary problem (Run 1).

The objective function J^P of the primary problem is a quadratic loss function with diagonal weighting matrix K^P. The planning horizon is T=10. The variables entering the objective function of the primary problem are listed for convenience in Table 1, together with the corresponding weights and desired values and with other endogenous variables of importance. In the table, X_t designates the (wildly fluctuating) historical values of the exports of goods and services in current prices. The variables G, R and TY are control variables. All variables except R are defined as growth rates.

TABLE 1

Main variables of the Uebe model

		Desired value	Weight
Y:	Gross social product i.c.p.	6	1
M:	Import of goods and services i.c.p.	$= X_t$	1
A:	Total number employed	1	1
PY:	Price index of gross social product (1962 = 100)	0	1
G:	Government expenditures i.c.p.	6	2
R:	Discount rate	5	2
TY:	Indirect taxes minus subsidies	0.7	2
D:	Amortization i.c.p.		
Q:	Gross income from entrepreneurial activity and assets		
LD:	Net income from non-independent work		
QD:	Net income from entrepreneurial activity and assets		

Sensitivity analysis: The cumulative sensitivity coefficients s

In the numerical application we assumed the true value of the matrix C to be known exactly and restricted our attention to disturbances of the matrices A and B. Before tackling the sensitivity reduction proper, we conducted the following simple, but revealing sensitivity analysis.

Let x_h be the h-th state variable and x_{ht} its value in period t. A measure for the influence of a small disturbance of an element a_{ij}

TABLE 2

The critical parameters of the model for selected values of x_h

$x_h = Y$		$x_h = PY$		$x_h = M$	
Parameter	Value of s	Parameter	Value of s	Parameter	Value of s
$a_{Y,D}$	106	$a_{PY,D}$	115	$a_{M,D}$	115
$a_{Y,Q}$	92	$a_{PY,Q}$	98	$a_{M,Q}$	98
$a_{Y,QD}$	75	$a_{PY,QD}$	81	$a_{M,QD}$	81
$b_{Y,G}$	65	$b_{PY,G}$	71	$b_{M,G}$	71
$a_{Y,Y}$	43	$a_{PY,Y}$	45	$a_{Y,D}$	59
$b_{Y,R}$	37	$b_{PY,R}$	41	$a_{Y,Q}$	46
$a_{LQ,D}$	25	$a_{PY,LQ}$	22	$a_{M,Y}$	45
$a_{Y,LQ}$	21	$a_{Q,D}$	16	$b_{M,R}$	41
$a_{LQ,Q}$	19	$a_{PY,A}$	15	$b_{Y,D}$	37
$b_{LD,G}$	16	$a_{Q,Q}$	12	$a_{Y,QD}$	37
$a_{LQ,QD}$	16	$b_{PY,TY}$	11	$a_{QD,D}$	30
$a_{Y,A}$	15	$b_{Q,G}$	10	$a_{Y,Y}$	24
$a_{A,D}$	15	$a_{Q,QD}$	10	$a_{QD,Q}$	23
$a_{A,Q}$	11	$a_{Y,D}$	6	$a_{M,LQ}$	22
$b_{Y,TY}$	11	$a_{Q,Y}$	6	$b_{Y,G}$	21
$b_{A,G}$	11	$a_{A,D}$	6	$b_{QD,R}$	19
$a_{LQ,Y}$	10	$b_{R,R}$	5	$a_{QD,QD}$	19
$a_{A,QD}$	9	$a_{Y,Q}$	5	$a_{M,A}$	15

of A (or b_{ij} of B) on the trajectory of x_h is

$$(21) \qquad s_{x_h}(a_{ij}) = \sum_{t=1}^{T} |\Delta x_{ht} / \Delta a_{ij}| .$$

The so defined coefficients s were calculated with $\Delta a_{ij} = 0.01 a_{ij}$ for all state variables x_h and all 99 non-zero elements of A and B, using the optimal feedback rule of Run 1 to generate x_t given x_{t-1}, $0 < t \leq T$. The elements of A resp. B corresponding to the NK highest values of s for a given x_h, that is, the <u>critical parameters</u> of the model, are listed in Table 2 for different values of x_h and NK = 18. In this table, $a_{Y,D}$ designates the parameter located in "row Y" and "column D" of matrix A, etc. Thus $a_{Y,D}$ expresses the direct "impact" of D_{t-1} on Y_t.

The results are not basically different for other choices of x_h. They vividly illustrate the generally recognized predominance of depreciation D and entrepreneurial income Q,QD in the model's dynamics. In the same vein, they suggest that G is the control variable with the strongest potential for giving rise to state disturbances; it is followed by the discount rate R.

The combined problem

In all optimizations presented here, α is defined as the vector of the NK critical parameters of A and B with respect to some state variable x_h. When not stated otherwise, NK = 18 and x_h = Y. In other words, the sensitivity reduction problem is taken to be the problem of countering the effect of perturbations of the 18 parameters of A and B most important for the behaviour of Y in the sense of (21). No dimensionality problem arises from the definition of α as a vector, as we use a directional derivative $\delta x_t / \delta\alpha$ in direction of the unit vector instead of NK partial derivatives $\partial x_t / \partial\alpha_j$. The sensitivity weighting matrix K^S is the unity matrix in all experiments; in every case presented T = 10.

The choice of the unit matrix for K^S and of the unit vector as direction of the derivative $\delta x_t / \delta\alpha$ is completely arbitrary. Other choices may appear more natural or better justifiable. One might for example define the direction of $\delta\alpha$ in function of the empirical variances of the model's parameters; or weight the sensitivity terms corresponding to Y more heavily than those corresponding to other variables, since the choice of Y as "reference variable" in the determination of the critical parameters hints at a particular interest in the corresponding trajectory sensitivity. Such more complicated weighting schemes were used in alternative experiments; they did not lead to results qualitatively different from those presented here.

As scalar measures for the importance of open-loop and closed-loop sensitivity, in the following we use the variables

$$\text{(22)} \qquad \text{RHO} := \sum_{t=1}^{10} \rho_t' \rho_t \,, \qquad \text{SIG} := \sum_{t=1}^{10} \tilde{\sigma}_t' \tilde{\sigma}_t \,,$$

$$\text{CON} := \sum_{t=1}^{10} \bar{\sigma}_t' \bar{\sigma}_t$$

where $\tilde{\sigma}_t$ resp. $\bar{\sigma}_t$ designates the elements of σ_t which do not (do) correspond to $\delta u_t / \delta\alpha$.

Results

In all optimization experiments the approximation of σ by ρ was satisfactory except for very large values of λ--this point will be discussed in more detail later. Most important, σ_t kept pace with ρ_t as RHO decreased with increasing values of λ. This is reflected in Figures 1 and 2 (Figure 2 being essentially a blow-up of Figure 1).

Both figures suggest that the practically relevant trade-offs between sensitivity reduction and primary economic performance are to be found in the approximate range $10 \leq \lambda \leq 10^4$. For smaller values of λ one hardly observes any sensitivity reduction or increase in the welfare loss. For values of λ superior to 10^4 seemingly negligible reductions of RHO and SIG become exceedingly costly in terms of J^P. Only in the range $10 \leq \lambda \leq 10^2$ can one observe a strong sensitivity reduction which is not associated with a large loss in primary performance. The "relevant trade-off range" appears fairly independent of the number of critical parameters considered; see Figure 3. However, both the open-loop and the closed-loop sensitivities increase and their reduction becomes more costly with large values of NK.

The results presented are those obtained after the second iteration according to (19). Further iterations bring only minor improvements with them. Moreover, one should note that the approximation of σ by ρ breaks down and that the iterative updating according to (20) diverges for large values of λ. The values of λ for which this happens are lower, the larger NK is (ca. $\lambda = 10^5$ for NK = 30, $\lambda = 10^7$ for NK = 18, ...). A possible reason for this may be found in Table 3, which refers again to the situation NK = 18: Beginning approximatively with $\lambda = 10^7$, the importance of the closed-loop control sensitivity $\delta u_+ / \delta\alpha$ (expressed by CON) relative to the non-control sensitivity (expressed by SIG) increases sharply. However, the non-control sensitivity is ignored in the open-loop formulation. In any case, the divergence problem for large λ's does not appear serious, since it occurs for values of λ which presumably lie outside the practically relevant range.

Table 3 shows also how the control effort varies with λ. One should recognize, however, that an economically meaningful comparison of the control effort values or of any other value derived from J^P presupposes that J^P is a correct representation of the "true" economic preferences over the whole set of trajectories considered. We shall not discuss here the associated difficulties.

Finally, Figures 4-6 show the optimal open-loop trajectories of the control variables for $\lambda = 0$, $\lambda = 10^3$ and $\lambda = 10^4$. Reduced sensitivity seems to imply both a diminution of the government's expenditures and a more expansive monetary policy as expressed by a lower discount rate. The changes in the optimal values of the (somewhat problematic) variable TY do not follow any easily recognizable pattern.

TABLE 3

Control efforts and relative importance of the control sensitivity

λ	CON/SIG (in%)	Control effort $\sum_{t=1}^{N} (u_t - \bar{u}_t)'(u_t - \bar{u}_t)$
0	0.8	78
1	0.8	72
10	0.8	76
10^2	0.7	70
10^3	0.8	72
10^4	0.8	335
10^5	11	569
10^6	15	664
10^7	25	836

To a certain extent Figures 4-6 are misleading. Not all the coefficients of the matrix G_t and the optimal values of the control variables change monotonically as λ is increased from 0 to higher values. Reversals of the direction of change are possible (we observed at most one such reversal for any given element of G_t). At the moment we cannot exclude that this behaviour results from the fact that we derive an approximative solution rather than from basic properties of the optimal solution's structure.

Very similar results to those presented here are obtained if one bases the definition of the critical parameters on another variable x_h rather than on Y. In addition to the optimization mentioned here we conducted different deterministic and stochastic simulations to study the trajectory disturbances resulting from large and/or random parameter disturbances. These simulations strongly suggest that the sensitivity reduction approach presented here, although formally based on small parameter disturbances, effectively reduces the trajectory sensitivity even in the case of fairly large (±10% or more) parameter disturbances. Moreover, the sensitivity of the value of

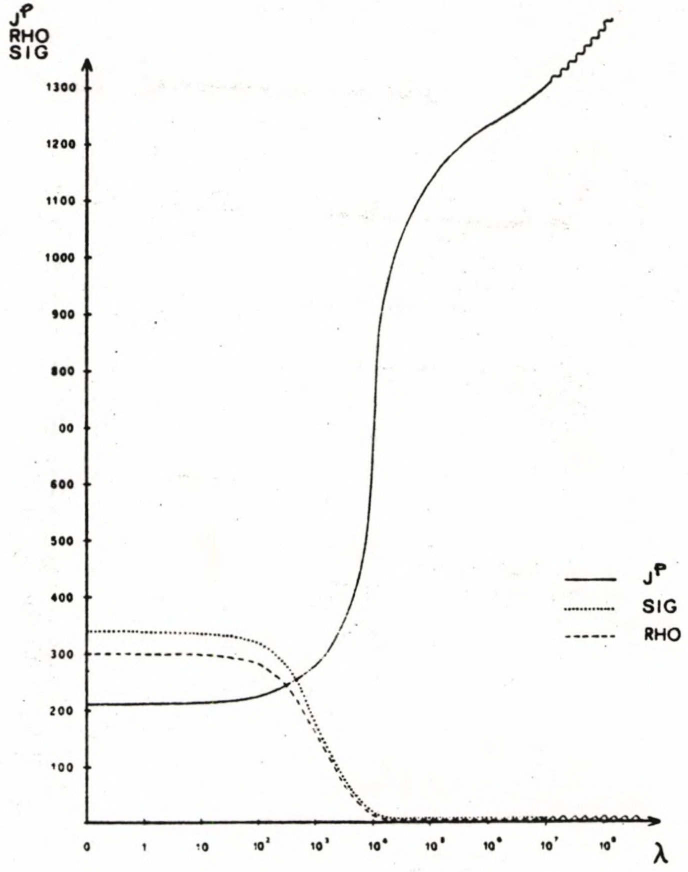

Figure 1: The behaviour of J^P, RHO and SIG as functions of λ

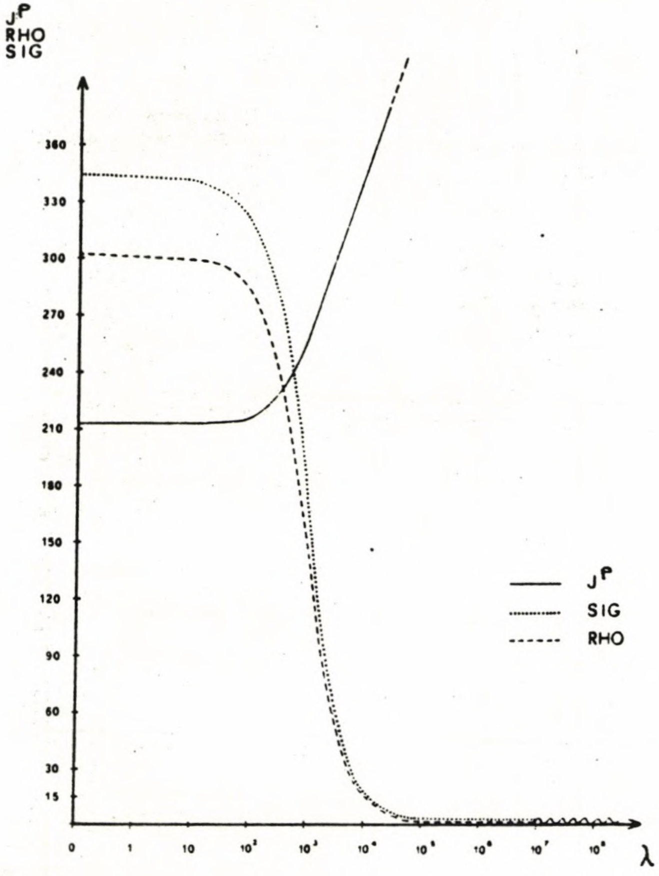

Figure 2: The behaviour of J^P, RHO and SIG as functions of λ

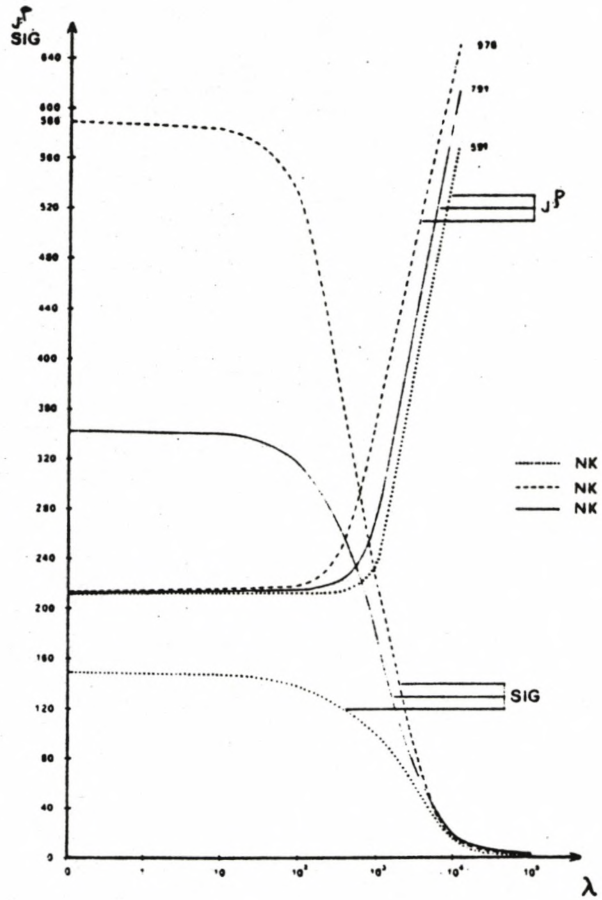

Figure 3: The influence of NK on SIG and J^ρ

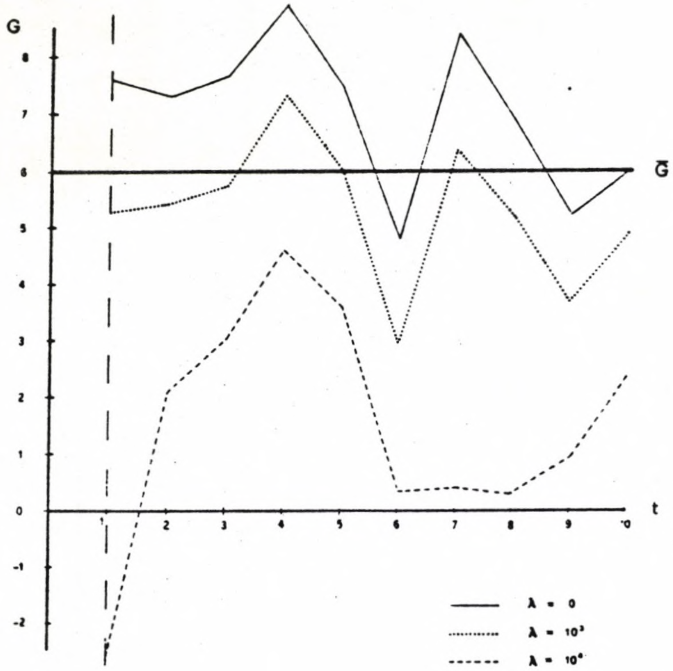

Figure 4: The optimal government's expenditure G for alternative values of λ

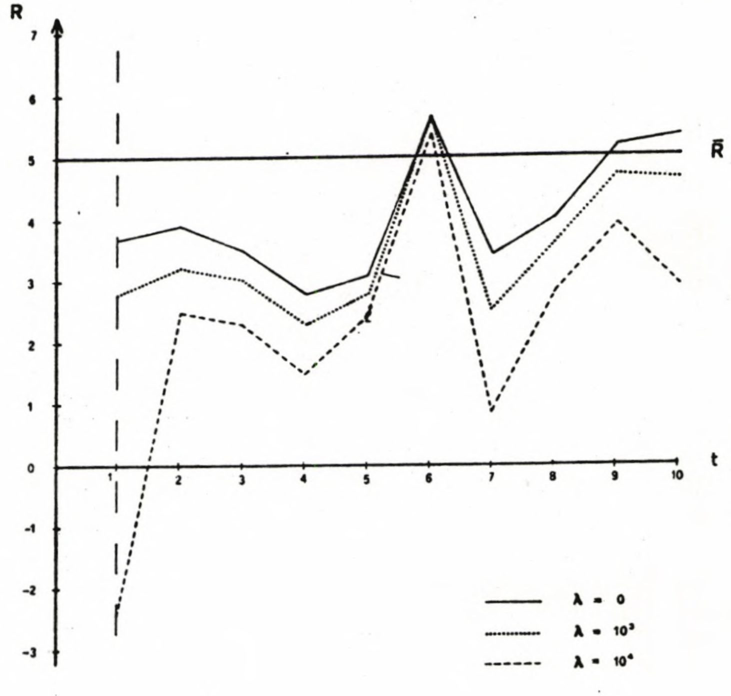

Figure 5: The optimal discount rate R for alternative values of λ

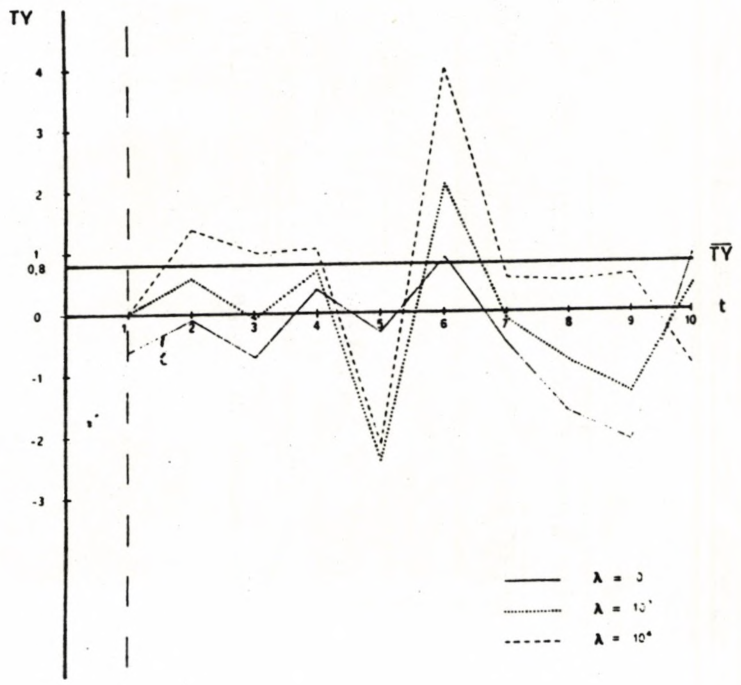

Figure 6: The optimal taxes for alternative values of λ

the objective function is simultaneously reduced. These numerical results will be presented in a subsequent paper together with some related analytical results.

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