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RECURSIVE CONTRACTS

ALBERT MARCET
Department of Economics, University College London, Barcelona GSE, and CEPR

RAMON MARIMON
Department of Economics and RSCAS, European University Institute, Department of Economics and Business, UPF, Barcelona GSE, NBER, and CEPR

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We obtain a recursive formulation for a general class of optimization problems with *forward-looking* constraints which often arise in economic dynamic models, for example, in contracting problems with incentive constraints or in models of optimal policy. In this case, the solution does not satisfy the Bellman equation. Our approach consists of studying a recursive Lagrangian. Under standard general conditions, there is a recursive *saddle-point* functional equation (analogous to a Bellman equation) that characterizes a recursive solution to the planner's problem. The recursive formulation is obtained after adding a co-state variable μ_t summarizing previous commitments reflected in past Lagrange multipliers. The continuation problem is obtained with μ_t playing the role of weights in the objective function. Our approach is applicable to characterizing and computing solutions to a large class of dynamic contracting problems.

KEYWORDS: Recursive methods, dynamic optimization, Ramsey equilibrium, time inconsistency, limited commitment, limited enforcement, saddle-points, Lagrangian multipliers, Bellman equations.

1. INTRODUCTION

RECURSIVE METHODS have become a basic tool for the study of dynamic economic models. For example, Stokey, Lucas, and Prescott (1989) and Ljungqvist and Sargent (2018) described a large number of applications to macroeconomic models. Under standard assumptions, the optimal solution has a recursive formulation; more precisely, it satisfies $a_t = \psi(x_t, s_t)$, where a_t denotes actions, s_t the exogenous shock to the economy, and x_t is a small set of endogenous state variables. Importantly, ψ is a *time-invariant* policy function derived from the *Bellman equation*. We refer to this as the "standard dynamic programming" case. As is well known, in this case the solution is time-consistent.

A key assumption needed to obtain the Bellman equation is that the feasible set for a_t is constrained only by (x_t, s_t). Unfortunately, many economic problems of interest do not satisfy this requirement and they include *forward-looking constraints*, where future actions a_{t+n} also constrain the feasible set of a_t. This occurs, for example, in problems where

Albert Marcet: a.marcet@ucl.ac.uk
Ramon Marimon: ramon.marimon@eui.eu

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the principal chooses a contract subject to intertemporal participation constraints (see Example 1 below), and in models of optimal policy under equilibrium constraints (see Example 2 below). Many dynamic games share the same feature.

In the presence of forward-looking constraints, optimal plans typically do not satisfy the Bellman equation and the solution does not have a standard recursive form. The reason is that the choice for a_t carries with it an implicit promise about a_{t+n}; therefore, contracting parties need to keep track of some additional variables summarizing commitments made in the past about today's choice. The absence of a standard recursive formulation greatly complicates the analysis and numerical solution.

In this paper, we provide an integrated approach for a recursive formulation of a large class of dynamic maximization problems with forward-looking constraints. Our interest lies in solving a maximization problem $\mathbf{PP}_\mu$ that depends on certain weights μ. A contribution of the paper is to show that the optimal solution is obtained by solving at each point in time t a continuation planner's problem $\mathbf{PP}_{\mu_t}$ (note that μ now has a subscript t) where the evolution of the weight μ_t is associated with the Lagrange multipliers of the forward-looking constraints; the forward-looking constraints are embedded in the objective function of this continuation problem.

We obtain a *saddle-point functional equation* (**SPFE**) which is an analog of the Bellman equation, with the important difference that, while the Bellman equation solves a maximization problem, the **SPFE** solves a saddle-point problem, as its name indicates. We then show *necessity*; that is, under standard general conditions, solutions to $\mathbf{PP}_\mu$ satisfy $a_t = \psi(x_t, \mu_t, s_t)$ for a time-invariant *policy function* ψ, or a selection from a *policy correspondence* Ψ, which solves the **SPFE** with the weights μ following a pre-specified law of motion. We also prove *sufficiency*; that is, solutions to the **SPFE** solve the planning problem of interest $\mathbf{PP}_\mu$, when the value function of **SPFE** is differentiable in μ_t for every (x_t, μ_t, s_t), a property which is satisfied when the solution for a_t in the SPFE is unique. For more general cases (e.g., non-concave problems, or non-differentiable value functions, possibly with multiple solutions), we provide an *intertemporal consistency condition* (**ICC**) guaranteeing sufficiency. We show that when **SPFE** has solutions, there is one satisfying **ICC**, which is easily obtained in computed solutions. Finally, we also provide conditions for the existence of saddle-point solutions to **SPFE** and show how standard dynamic programming results—such as the contraction property implying uniqueness of the value function—naturally extend to our **SPFE**.

The fact that our formulation is based on standard optimization and dynamic programming tools facilitates the analysis and permits the application of a number of algorithms to obtain numerical solutions for dynamic stochastic models. For example, for a large class of models, accounting for forward-looking constraints translates into introducing time-varying Pareto weights into the objective function of $\mathbf{PP}_\mu$. The time-varying co-state μ_t enters as a *wedge* in the *stochastic discount factor* of $\mathbf{PP}_\mu$, showing the intertemporal distortions due to the presence of forward-looking constraints.

$\mathbf{PP}_{\mu_t}$, with a given initial condition (x_t, s_t), is labeled as the *continuation problem* because its solution coincides with the solution from period t onwards of the original problem $\mathbf{PP}_\mu$. Having this continuation problem at hand is at the core of the proof that the **SPFE** holds, and it facilitates the interpretation of time-inconsistent models. This continuation problem signals some practical advantages of our approach. A commonly used tool for solving models with forward-looking constraints has been the promised-utility approach described in the pioneering works of Abreu, Pearce, and Stacchetti (1990), Green (1987), and Thomas and Worrall (1988). A difficulty in using this approach to find numerical solutions is that promised utilities need to be restricted so as to guarantee that the continuation problem is well defined. Computing the set of feasible utilities is often a major difficulty. But—under standard assumptions—the continuation problem $\mathbf{PP}_{\mu'}$ has a solution for *any* $\mu' \geq 0$; thus, our approach sidesteps the computation of the set of feasible promised utilities. As we also discuss below, in many cases a recursive formulation in our approach is obtained with fewer decision variables and even fewer state variables than with promised utilities, allowing for a more efficient computation.

Our approach has already been used in many applications. A few examples are: growth and business cycles with possible default (Marcet and Marimon (1992), Kehoe and Perri (2002), Cooley, Marimon, and Quadrini (2004)); social insurance (Attanasio and Rios-Rull (2000)); optimal fiscal and monetary policy design with incomplete markets (Aiyagari, Marcet, Sargent, and Seppälä (2002), Svensson and Williams (2008)); and political-economy models (Acemoglu, Golosov, and Tsyvinskii (2011)). Furthermore, the introduction of the co-state variable μ_t to account for forward-looking constraints has proved to be a powerful instrument for analyzing and comparing other economies with frictions (Chien, Cole, and Lustig (2012)) and, in particular, in pricing contracts that endogenize forward-looking constraints or other frictions (Alvarez and Jermann (2000), Krueger, Perri, and Lustig (2008)).

Section 2 provides a basic introduction to our approach. The main body of the theory is in Sections 3 and 4 of this paper, while most proofs are in the Appendix. The relation to the literature and the promised utility approach are discussed in Section 5. Section 6 concludes.

2. FORMULATING CONTRACTS AS RECURSIVE SADDLE-POINT PROBLEMS

In this section, we provide an outline of our approach. We show how dynamic programming methods can be extended to find a recursive formulation for a large class of models with forward-looking constraints. We leave the formal results to Sections 3 and 4. This section should be self-sufficient for a user of the method.

The class of models under study is characterized as dynamic planning problems ($\mathbf{PP}_\mu$) with a return function as follows:

$$\mathbf{PP}_\mu: \quad V_\mu(x_0, s_0) = \sup_{\{a_t, x_t\}} \mathrm{E}_0 \sum_{j=0}^{l} \sum_{t=0}^{N_j} \beta^t \mu^j h_0^j(x_t, a_t, s_t) \tag{1}$$

$$\text{s.t. } x_{t+1} = \ell(x_t, a_t, s_{t+1}), \qquad p(x_t, a_t, s_t) \geq 0 \quad \text{all } t \geq 0, \tag{2}$$

$$\mathrm{E}_t \sum_{n=1}^{N_j+1} \beta^n h_0^j(x_{t+n}, a_{t+n}, s_{t+n}) + h_1^j(x_t, a_t, s_t) \geq 0, \quad j = 0, \dots, l,$$
$$\text{all } t \geq 0, \text{ given } (x_0, s_0). \tag{3}$$

Here ℓ, p, h_0, h_1 are known functions; β, x_0, s_0 and $\mu \equiv (\mu^0, \dots, \mu^l) \in R_+^{l+1}$ are known constants or vectors, and $\{s_t\}_{t=0}^\infty$ an exogenous stochastic Markov process. We denote as h_i^j the jth element of the function h_i for $i = 0, 1$. The solution is a *plan*[1] $\boldsymbol{a} \equiv \{a_t\}_{t=0}^\infty$, where $a_t(s^t) \in A \subset R^m$ is a state-contingent action; as usual, we take $s^t = (s_0, \dots, s_t)$.

The *forward-looking constraints* (3) are at the core of our analysis. We only consider $N_j = 0$ or ∞. Without loss of generality, we assume $N_j = \infty$ for $j = 0, \dots, k$, and $N_j = 0$ for $j = k+1, \dots, l$ for a nonnegative $k < l$. Note that this implies $N_0 = \infty$.

[1]We use bold notation to denote sequences of measurable functions.

The case $N_j = \infty$ covers a large class of problems where discounted present values are part of the constraint, as in models with intertemporal participation constraints (see Example 1 below). Constraints with $N_j = 0$ cover cases where the planner must take into acccount intertemporal reactions of agents, as in dynamic Ramsey equilibria (see Example 2 below).[2]

Letting $(\boldsymbol{a}^*, \boldsymbol{x}^*) = \{a_t^*, x_t^*\}_{t=0}^{\infty}$ denote a solution of PP_μ at (x_0, s_0), the value of the objective function—parameterized by μ—is given by $V_\mu(x_0, s_0) \equiv E_0 \sum_{j=0}^{l} \sum_{t=0}^{N_j} \beta^t \mu^j h_0^j(x_t^*, a_t^*, s_t)$.

It is without loss of generality that the same function h_0 appears in the objective function and in the constraints (3).[3] Note also that even though μ could be normalized without affecting the solution (e.g., taking $\mu^0 = 1$), the value function V_μ is defined for all $\mu \in R_+^{l+1}$. Both of these features are needed to deliver the continuation problem that suitably characterizes a recursive solution in Proposition 1 below.

Standard dynamic programming considers the following special case of $\mathbf{PP}_\mu$: (i) forward-looking constraints (3) are absent or never binding, and (ii) the objective function is a discounted infinite sum, that is, $\mu^j = 0$ for $j > k$. As is well known, a standard *Bellman functional equation* holds in that case under very general assumptions.[4] This guarantees the powerful result that the optimal solution to $\mathbf{PP}_\mu$ satisfies $a_t^* = \psi_\mu(x_t^*, s_t)$ for a *time-independent* policy function ψ_μ derived from the Bellman equation. This result is very often used in the literature to characterize and compute solutions to $\mathbf{PP}_\mu$. Furthermore, the solution is time-consistent.

Unfortunately, as Kydland and Prescott (1977) pointed out, in the presence of forward-looking constraints (3), these dynamic programming results no longer hold, and the solution is often time-inconsistent.

2.1. *An Intuitive Argument*

We now provide an intuitive argument showing how the Lagrangian of (1) can be formulated in recursive form, with respect to the constraints (3). This formulation is very convenient technically and conceptually, since using a standard Lagrangian approach provides the basic framework to derive our recursive formulation and enlightens the key feature of our approach: forward-looking constraints can be summarized in a co-state vector, μ. A formal analysis is given in Section 3.

A Lagrangian of $\mathbf{PP}_\mu$ that incorporates forward-looking constraints can be written as

$$\mathcal{L}_\mu(\boldsymbol{a}, \boldsymbol{\gamma}; x_0, s_0) = \mathrm{E}_0 \Bigg[\sum_{j=0}^{l} \sum_{t=0}^{N_j} \beta^t \mu^j h_0^j(x_t, a_t, s_t) + \sum_{t=0}^{\infty} \beta^t \sum_{j=0}^{l} \gamma_t^j \mathrm{E}_t \sum_{n=1}^{N_j+1} \beta^n \big(h_0^j(x_{t+n}, a_{t+n}, s_{t+n}) + h_1^j(x_t, a_t, s_t) \big) \Bigg], \quad (4)$$

[2]Intermediate cases with finite $N_j > 0$ can be treated as a special case of $N_j = 0$. We discuss such a case at the end of Section 5.

[3]Example 2 below substantiates this claim.

[4]More precisely, the value function satisfies $V_\mu(x, s) = \sup_a \{\mu h_0(x, a, s) + \beta \mathrm{E}[V_\mu(x', s') \mid s]\}$ s.t. (2). We denote $\mu h_i(x, a, s) \equiv \sum_{j=0}^{l} \mu^j h_i^j(x, a, s)$.

where γ_t is the Lagrange multiplier associated with (3).[5] To simplify the exposition, the remaining constraints are imposed separately; hence, $\mathcal{L}_\mu$ is defined for $\boldsymbol{a}$ satisfying (2).

Using the law of iterated expectations to eliminate E_t and simple algebra, one can show that, for each argument $(\boldsymbol{a}, \boldsymbol{\gamma})$, we can rewrite $\mathcal{L}_\mu$ as[6]

$$\mathcal{L}_\mu(\boldsymbol{a}, \boldsymbol{\gamma}; x_0, s_0) = \mathrm{E}_0\left[\sum_{t=0}^{\infty} \beta^t\big[\mu_t h_0(x_t, a_t, s_t) + \gamma_t h_1(x_t, a_t, s_t)\big]\right], \tag{5}$$

where $\mu_{t+1} = \varphi(\mu_t, \gamma_t)$ for $\varphi : R_+^{l+1} \to R_+^{l+1}$ given by

$$\begin{aligned} \varphi^j(\mu, \gamma) &\equiv \mu^j + \gamma^j \quad \text{for } j = 0, \dots, k, \\ &\equiv \gamma^j \quad \text{for } j = k+1, \dots, l, \end{aligned} \tag{6}$$

and with initial conditions $\mu_0 = \mu$.

Upon inspection of (5)–(6) and (2), it should be "intuitive" that $\mathcal{L}_\mu$ can yield a recursive structure similar to the programs amenable to dynamic programming; namely, the objective function (5) is a discounted sum with time-invariant return functions (h_0, h_1) and past shocks enter into the transition functions (6) and (2), and into the return function at t, only through the "state variables" (x_t, μ_t). This interpretation relies on the fact that $(\boldsymbol{a}, \boldsymbol{\gamma})$ are decision variables of the Lagrangian and on the introduction of $\boldsymbol{\mu} \equiv \{\mu_t\}_{t=0}^{\infty}$ as a co-state variable with transition function given by (6). This suggests that, to the extent that solutions of $\mathcal{L}_\mu(\cdot; x_0, s_0)$ are solutions to $\mathbf{PP}_\mu$, the solution we seek satisfies $(a_t, \gamma_t) = \psi(x_t, \mu_t, s_t)$ for some time-invariant function ψ.

2.2. *An Alternative Functional Equation*

The intuition in the previous paragraph cannot be formalized by appealing to standard dynamic programming. This is because the Bellman equation is shown to hold for dynamic *maximization* problems, but the above Lagrangian—that is, (5) subject to (6)–(2)—gives the desired solution to $\mathbf{PP}_\mu$ if we find the *saddle-point* of that Lagrangian. Therefore, to conclude that the solution to $\mathbf{PP}_\mu$ has a recursive formulation including μ_t as a co-state, one needs to derive an analogous functional equation for saddle-point problems. The task of this paper is to prove the connection between the saddle-point functional equation and the problem of interest $\mathbf{PP}_\mu$.

To this end, we first introduce *notation for saddle-point problems*. Given a function $\mathcal{F} : Y \times Z \longrightarrow R$, we define a *saddle-point of* $\mathcal{F}$ as $(y^*, z^*) \subset Y \times Z$ satisfying

$$\mathcal{F}\big(y^*, z\big) \ge \mathcal{F}\big(y^*, z^*\big) \ge \mathcal{F}\big(y, z^*\big) \quad \text{for any } z \in Z \text{ and } y \in Y. \tag{7}$$

The problem of finding such a (y^*, z^*) is called a *saddle-point problem*, which we denote as

$$\mathrm{SP} \inf_{z \in Z} \sup_{y \in Y} \mathcal{F}(y, z).$$

[5]In fact, we should refer to γ_t as a "normalized" multiplier. Strictly speaking, the Lagrange multiplier of the jth constraint (2) at t for a realization s^t is given by $\beta^t \gamma_t(s^t) P(s^t \mid s_0)$, where P is the probability measure (or density)of s^t.

[6]See Appendix A for the algebra.

The set of (potentially multiple) saddle-points (y^*, z^*) that solve this problem is denoted

$$\arg \mathrm{SP} \inf_{z\in Z} \sup_{y\in Y} \mathcal{F}(y, z).$$

Note that there is no ordering or sequentiality of the inf and sup operators in the above definition: a saddle-point satisfies both inequalities in (7) simultaneously; "inf" and "sup" in this definition only denote which variables are on the right or the left side in the string of inequalities (7).[7]

We now define a functional equation analog to Bellman's that characterizes recursively a saddle-point of $\mathcal{L}_\mu$, denoted $(\boldsymbol{a}^*, \boldsymbol{\gamma}^*)$. This will be useful because, as is well known, under suitable conditions, $\boldsymbol{a}^*$ is then a solution to $\mathbf{PP}_\mu$ and $\boldsymbol{\gamma}^*$ are the Lagrange multipliers of constraints (3).

We show that the saddle-point value function $W : X \times R_+^{l+1} \times S \to R$ defined as $W(x, \mu, s) = \mathcal{L}_\mu(\boldsymbol{a}^*, \boldsymbol{\gamma}^*)$ satisfies the following *saddle-point functional equation*:

SPFE

$$W(x, \mu, s) = \mathrm{SP} \inf_{\gamma\geq 0} \sup_{a\in A} \{\mu h_0(x, a, s) + \gamma h_1(x, a, s) + \beta \mathrm{E}[W(x', \mu', s')|s]\} \tag{8}$$

$$\text{s.t. } x' = \ell(x, a, s'), \qquad p(x, a, s) \geq 0, \tag{9}$$

$$\text{and} \quad \mu' = \varphi(\mu, \gamma). \tag{10}$$

Given a value function W satisfying this **SPFE** in any possible state $(x, \mu, s) \in X \times R_+^{l+1} \times S$, the corresponding saddle-point policy correspondence (*SP policy correspondence*) is defined as

$$\Psi_W(x, \mu, s) = \arg \mathrm{SP} \inf_{\gamma\geq 0} \sup_{a\in A} \{\mu h_0(x, a, s) + \gamma h_1(x, a, s) + \beta \mathrm{E}[W(x', \mu', s')|s]\}$$

subject to (9)–(10).[8]

Note that (8) has three additional features that are not found in the Bellman equation: (i) it is a saddle-point problem rather than a maximization problem; (ii) μ is an argument of the value function W, and (iii) the law of motion for μ is added as a constraint.

As with the Bellman equation, the **SPFE** gives the solution we seek. Our approach is to show, first, necessity of **SPFE**, namely, that, under standard assumptions (convexity of the constrained set, etc.), a solution to $\mathbf{PP}_\mu$, $\{a_t^*\}_{t=0}^\infty$, satisfies $(a_t^*, \gamma_t^*) \in \Psi_W(x_t^*, \mu_t^*, s_t)$, for some $\gamma_t^* \geq 0$. If, in addition, Ψ_W is single valued, we denote the resulting function by ψ_W, the solution satisfies $(a_t^*, \gamma_t^*) = \psi_W(x_t^*, \mu_t^*, s_t)$, and we call it a *saddle-point policy function* (*SP policy function*). Furthermore, the value function of $\mathbf{PP}_\mu$ satisfies this functional equation, that is, $W(x, \mu, s) = V_\mu(x, s)$ satisfies the **SPFE** (Theorem 1).

[7]For clarity, we denote $\inf_{z\in Z}[\sup_{y\in Y} \mathcal{F}(y, z)]$ a sequential problem where first one finds $\sup_{y\in Y} \mathcal{F}(y, z)$ for each given z and the resulting sup (itself a function of z) is minimized over z. It is well known that the ordering may matter for this sequential problem, that is, it may be that $\arg\inf[\sup \mathcal{F}] \neq \arg\sup[\inf \mathcal{F}]$ and $\inf[\sup \mathcal{F}] \neq \sup[\inf \mathcal{F}]$, and in this case, a saddle-point may not exist. We focus on problems where the saddle-point exists, and provide conditions guaranteeing existence (Theorem 3).

[8]For an explicit definition of the saddle-point inequalities, see (19) and (20) in Section 3.

We also provide a set of general conditions[9] guaranteeing sufficiency of **SPFE,** namely, that if a value function W satisfies (8) for all (x, μ, s), and $(\boldsymbol{a}^{**}, \boldsymbol{\gamma}^{**})$ satisfies $(a_t^{**}, \gamma_t^{**}) \in \Psi_W(x_t^{**}, \mu_t^{**}, s_t)$, then $\boldsymbol{a}^{**}$ is a solution of $\mathbf{PP}_\mu$.[10]

In sum, from the user's perspective, what needs to be retained is that a recursive solution is obtained by adding a co-state variable μ that is a function of the Lagrange multiplier of the forward-looking constraints in previous periods. As seen from (6), this state variable follows the recursion $\mu_{t+1}^{j,*} = \mu_t^{j,*} + \gamma_t^{j,*}$ for $j \leq k$ (i.e., for constraints involving discounted sums with $N_j = \infty$), and it is the previous multiplier $\mu_{t+1}^{j,*} = \gamma_t^{j,*}$ for $j > k$ (i.e. for constraints involving one future period with $N_j = 0$). One needs to initialize $\mu_0^* = \mu$.

The examples in Sections 2.2.2 and 2.2.3 show how this idea can be applied to obtain recursive solutions in problems with forward-looking constraints.

2.2.1. *Time-Inconsistency and the Continuation Problem*

In programs where the standard Bellman equation applies, the program is time-consistent: reoptimization at the new state in future periods is also a continuation solution from the original state. However, as is well known, in the presence of forward-looking constraints (3), the solution may be time-inconsistent: the value of a_1^* for a given realization of s_1 differs from the value a_0^* that would optimize $\mathbf{PP}_\mu$ if initial conditions at $t = 0$ were (x_1^*, s_1).[11]

The key to our approach will be that if one optimizes $\mathbf{PP}_{\mu_1^*}$ (note the subscript is now μ_1^*) with initial conditions (x_1^*, s_1), the solution coincides with the continuation of the original solution $\{a_t^*, x_t^*\}_{t=1}^\infty$. To see this intuitively, expand the above Lagrangian (5):

$$\begin{aligned}
\mathcal{L}_\mu(\boldsymbol{a}, \boldsymbol{\gamma}; x_0, s_0) &= \mathrm{E}_0\left[\sum_{t=0}^{\infty} \beta^t \big[\mu_t h_0(x_t, a_t, s_t) + \gamma_t h_1(x_t, a_t, s_t)\big]\right] \\
&= \mathrm{E}_0\big[\mu_0 h_0(x_0, a_0, s_0) + \gamma_0 h_1(x_0, a_0, s_0) \\
&\quad + \beta \sum_{t=0}^{\infty} \beta^t \big[\mu_{t+1} h_0(x_{t+1}, a_{t+1}, s_{t+1}) + \gamma_{t+1} h_1(x_{t+1}, a_{t+1}, s_{t+1})\big]\big] \\
&= \mu_0 h_0(x_0, a_0, s_0) + \gamma_0 h_1(x_0, a_0, s_0) + \beta \mathrm{E}_0\big[\mathcal{L}_{\mu_1}\big(\boldsymbol{a}', \boldsymbol{\gamma}'; x_1, s_1\big)\big],
\end{aligned}$$

where $\boldsymbol{a} \equiv \{a_t\}_{t=0}^\infty$, and $\boldsymbol{a}' \equiv \{a_t\}_{t=1}^\infty$ denotes its continuation, similarly for $\boldsymbol{\gamma}$ and $\boldsymbol{\gamma}'$. That is, if (a_0^*, γ_0^*) is the first component of a saddle-point of $\mathcal{L}_\mu(\cdot; x_0, s_0)$ determining $x_1^* = \ell(x, a_0^*, s_1)$ and $\mu_1^* = \varphi(\mu, \gamma_0^*)$, then the saddle-point of $\mathcal{L}_{\mu_1^*}(\cdot; x_1^*, s_1)$ must coincide with $(\boldsymbol{a}^{*\prime}, \boldsymbol{\gamma}^{*\prime})$.[12] Furthermore, $\mathcal{L}_{\mu_1^*}(\boldsymbol{a}^{*\prime}, \boldsymbol{\gamma}^{*\prime}; x_1^*, s_1)$ is the Lagrangian of $\mathbf{PP}_{\mu_1^*}$ at (x_1^*, s_1), therefore the solution of $\mathbf{PP}_{\mu_1^*}$ coincides with the "sup" argument of the saddle-point of $\mathcal{L}_{\mu_1^*}$. A formal argument is given in Proposition 1.

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[9] As we show in Section 3, the constrained set may not be convex.

[10] We are ignoring, in this informal description, some delicate issues related to the fact that Ψ_W may be empty or it may be a multi-valued correspondence.

[11] More formally, leaving explicit the dependence on initial conditions, let $\{a_t^*(x_0, s^t)\}_{t=0}^\infty$ denote the solution of $\mathbf{PP}_\mu$. Then, absent forward-looking constraints, time-consistency holds; in particular, $a_0^*(\ell(x_0, a_0^*(x_0, s_0), s_1), s_1)) = a_1^*(x_0, s^1)$. With forward-looking constraints, this equality may not hold.

[12] This is because if the saddle-point of $\mathcal{L}_{\mu_1^*}$ differed from $(\boldsymbol{a}^*, \boldsymbol{\gamma}^*)$, then the latter would not be a saddle-point of $\mathcal{L}_\mu$, since the continuation of $\mathcal{L}_\mu$ satisfies all the constraints and has the same objective function as $\mathcal{L}_{\mu_1^*}$.

In this sense, we can say that in our approach, $\mathbf{PP}_{\mu_1^*}$ is a continuation problem. This gives the following characterization of time-inconsistency: in cases when $\mu_1^* \neq \mu$ (i.e., $\gamma_0^* \neq 0$), the solution to $\mathbf{PP}_\mu$ at (x_1^*, s_1) is generally time-inconsistent; obviously, these are precisely the cases where forward-looking constraints are binding.

The transition $\mathbf{PP}_{\mu_t^*} \to \mathbf{PP}_{\mu_{t+1}^*}$ captures several advantages of our approach. First, we use it as a step in proving the necessity of **SPFE**. Second, it shows one key advantage over the promised utility approach of Abreu, Pearce, and Stachetti: the only constraint on the co-state variable is that $\mu_t \in R_+^{l+1}$, under mild standard assumptions the continuation problem $\mathbf{PP}_{\mu_{t+1}^*}$ has a solution for *all* $\mu_{t+1} \in R_+^{l+1}$, as it involves maximizing a continuous objective function over a compact set. This sidesteps the complications of having to find the set of feasible promised utilities; we give a more thorough discussion in Section 5. Third, $\mathbf{PP}_{\mu_t^*}$ provides a natural way to check for time-consistency: the solution to $\mathbf{PP}_\mu$ is time-consistent when its objective function coincides with (or is proportional to) the objective function of $\mathbf{PP}_{\mu_1^*}$. Fourth, our approach often provides a useful economic intuition about how to design optimal contracts (institutions or mechanisms) subject to intertemporal incentive constraints and on how to "price" the costs of these constraints, in order to decentralize these contracts.

2.2.2. *Example 1: Risk-Sharing With Limited Enforcement*

Consider a model of a partnership with limited enforcement, where several agents can share their individual risks and jointly invest in a project which can only be undertaken jointly. There is a single consumption good and $l+1$ infinitely-lived consumers indexed by $j = 0, \ldots, l+1$ with standard preferences $E_0 \sum_{t=0}^{\infty} \beta^t u(c_t^j)$, where c is individual consumption. Agent j receives a random endowment of consumption good y_t^j at time t, $y_t = (y_t^0, \ldots, y_t^l)$. Agent j has an outside option that delivers total utility $v_j^a(y_t)$ if he leaves the contract in period t, where v_j^a is some known function.[13] Production of the consumption good is $F(k, \theta)$, where k is capital and θ a productivity shock. Production can be split into consumption c and investment i; capital depreciates at the rate δ. The process $\{\theta_t, y_t\}_{t=0}^{\infty}$ is assumed to be jointly Markovian and the initial conditions (k_0, θ_0, y_0) are given; c_t and i_t are chosen given information on (θ^t, y^t).

The planner solves

$$\max_{\{c_t, i_t\}} \mathrm{E}_0 \sum_{t=0}^{\infty} \beta^t \sum_{j=0}^{l} \alpha^j u(c_t^j)$$

$$\text{s.t. } k_{t+1} = (1-\delta)k_t + i_t, \tag{11}$$

$$F(k_t, \theta_t) + \sum_{j=0}^{l} y_t^j \geq \sum_{j=0}^{l} c_t^j + i_t, \quad \text{and}$$

$$\mathrm{E}_t \sum_{n=0}^{\infty} \beta^n u(c_{t+n}^j) \geq v_j^a(y_t), \quad \text{for all } j = 0, \ldots, l \text{ and } t \geq 0, \tag{12}$$

[13] A common assumption is that the outside option is autarky, where agent j consumes only his endowment from t onwards, $v_j^a(y_t) = \mathrm{E}[\sum_{n=0}^{\infty} \beta^n u(y_{t+n}^j) \mid y_t]$. It should be noted that one can allow for the outside option to be endogenous, for example, to exit and enter another partnership contract with some transitional cost, which requires to solve a fixed-point problem between the postulated outside options and the realised contracts (e.g., Cooley, Marimon, and Quadrini (2004)).

to find Pareto optimal allocations subject to enforcement constraints (12) and initial conditions (k_0, y_0, θ_0).

It is easy to map this planner's problem into our $\mathbf{PP}_\mu$ formulation if we take $\mu \equiv (\alpha^0, \dots, \alpha^l) \equiv \alpha$, $s \equiv (\theta, y)$; $x \equiv k$; $a \equiv (i, c)$; $\ell(x, a, s) \equiv (1-\delta)k + i$; $p(x, a, s) \equiv F(k, \theta) + \sum_{k=0}^l y^k - (\sum_{k=0}^l c^k + i)$; $h_0^j(x, a, s) \equiv u(c^j)$; $h_1^j(x, a, s) \equiv u(c^j) - v_j^a(y_t)$, $j = 0, \dots, l$.

The Lagrangian $\mathcal{L}_\mu$ can be found to be

$$\mathcal{L}_\mu(\boldsymbol{a}, \boldsymbol{\gamma}; k_0, y_0, \theta_0) = \mathrm{E}_0 \sum_{t=0}^\infty \beta^t \sum_{j=0}^l \big[\mu_{t+1}^j u\big(c_t^j\big) - \gamma_t^j v_j^a(y_t)\big],$$

for feasible consumption allocations. In this case, all the forward-looking constraints have $N_j = \infty$, hence $\mu_{t+1} = \mu_t + \gamma_t$ with initial conditions $\mu_0 = \alpha$.

The **SPFE** takes the form

$$\begin{aligned} &W(k, \mu, y, \theta) \\ &\quad = \mathrm{SP} \inf_{\gamma \geq 0} \sup_{c,i} \left\{ \sum_{j=0}^l \big[\mu^{j'} u\big(c^j\big) - \gamma^j v_j^a(y)\big] + \beta \mathrm{E}\big[W\big(k', \mu', y', \theta'\big)|y, \theta\big] \right\} \\ &\quad \text{subject to} \quad \mu' = \mu + \gamma, \end{aligned} \tag{13}$$

and feasibility constraints. Our results in Sections 3 and 4 guarantee that $W(k, \mu, y, \theta) = V_\mu(k, y, \theta)$ solves this functional equation and, recalling that ψ_W is the saddle-point that solves the SP problem in the right-hand side of (13), the solution to the problem of interest (11) satisfies

$$\begin{aligned} \big(\gamma_t^*, c_t^*, i_t^*\big) &= \psi_W\big(k_t^*, \mu_t^*, \theta_t, y_t\big) \quad \text{and} \\ \mu_{t+1}^* &= \mu_t^* + \gamma_t^*, \end{aligned} \tag{14}$$

with initial conditions $(k_0, \mu_0, \theta_0, y_0)$ where $\mu_0 = \alpha$.

The continuation problem $\mathbf{PP}_{\mu_1^*}$ replaces the objective function of (11) by $\mathrm{E}_1 \sum_{t=0}^\infty \times \beta^t \sum_{j=0}^l \mu_1^{j,*} u(c_t^j)$ for $\mu_1^* = \alpha + \gamma_0^*$ and initial conditions (k_1^*, y_1, θ_1), leaving technological and forward-looking constraints unchanged. This means that the solution after period $t = 1$ coincides with the solution of the original problem when the weights α of the agents in the objective function of (11) are replaced by the co-state variables μ_1^*; therefore, the variable μ_1^*, together with (k_1^*, y_1, θ_1), is all that needs to be remembered from the past at $t = 1$.

A solution to the continuation problem PP_{μ_1} exists generically for any $\mu_1 \in R_+^{l+1}$; therefore, we completely sidestep the complication of having to compute the set of feasible continuation promised utilities as would happen with the promised-utility approach—see Section 5.

The evolution of the weights μ_t^* determines agents' consumption. Every time that only the enforcement constraint for agent j is binding (e.g., $\gamma_t^{j,*} > 0$), given the optimality condition $\frac{u'(c_t^{j,*})}{u'(c_t^{i,*})} = \frac{\mu_t^{i,*}}{\mu_t^{j,*}}$, the ratio $\frac{c_t^{j,*}}{\sum_{i=0}^l c_t^i}$ increases "permanently." This avoids default while optimally smoothing consumption to the extent possible. This ratio will decrease in the future if the forward-looking constraint is binding for other agents.

Various papers in the literature have exploited these features to describe the evolution of consumption in several related setups.[14] Various contributions show how this planner's problem can be decentralized.[15]

The intertemporal Euler equation of $\mathbf{PP}_\mu$ at t is given by

$$\mu^j_{t+1} u'\big(c^j_t\big) = \beta \mathrm{E}_t\big[\mu^j_{t+2} u'\big(c^j_{t+1}\big)(F_{k_{t+1}} + 1 - \delta)\big]. \tag{15}$$

In the first best allocation, this equation holds for constant $\mu^j = \alpha^j$, for all j and t; hence, the μ's cancel out from this equation. The presence of time-varying μ in this equation shows how limited enforcement constraints introduce a wedge in agents' stochastic discount factors: $\beta \frac{\mu^j_{t+2} u'(c^j_{t+1})}{\mu^j_{t+1} u'(c^j_t)}$—that is, it shows how these constraints distort consumption allocations.

The existence of a time-invariant policy function (14) is key in finding numerical solutions guaranteeing that (15), the participation and the feasibility constraints hold. A useful property is that the vector μ_t can be normalized—for example, with $\widehat{\mu}^j_t = \mu^j_t / \sum_{i=0}^l \mu^i_t$. In Section 4, we provide conditions for the existence of a time-invariant policy function (Theorem 3).

2.2.3. *Example 2: A Ramsey Problem*

We present an abridged version of the optimal taxation problem under incomplete markets studied by Aiyagari at al. (2002). This example serves various purposes: it is an example of one-period forward-looking constraints when $N_j = 0$, it demonstrates that there is no loss of generality in having the same h_0 in the return and constraints, and it shows why we need a weight μ^0 in the first element of h_0 in the formulation of $\mathbf{PP}_\mu$. It will be useful also in Section 5 to compare our approach with the promised utility approach.

A government must finance exogenous random expenditures g with labor tax rates τ and issuing real riskless bonds b, given initial bonds b_0. A representative consumer maximizes utility $E_0 \sum_{t=0}^\infty \beta^t [u(c_t) + v(e_t)]$ subject to a budget constraint $c_t + b_{t+1} p^b_t = e_t(1 - \tau_t) + b_t$. Here c is consumption and e is effort (e.g., hours worked), p^b_t is the bond price, and τ_t tax rates. The process $\{g_t\}_{t=0}^\infty$ is Markovian and, since government bonds b_t are not contingent, markets are incomplete. Feasible allocations satisfy $c_t + g_t = e_t$. The bond and labor markets are competitive and $(g_0, \dots, g_t)$ is public information at t. The government's budget mirrors that of the representative agent; Ponzi games are ruled out.

In a Ramsey equilibrium, the government chooses optimal taxes and debt subject to competitive equilibrium and full commitment. Using a familiar argument, one can substitute out bond prices and taxes by equilibrium relationships so that the Ramsey equilibrium can be found by solving

$$\max_{\{c_t, b_t\}} E_0 \sum_{t=0}^\infty \beta^t \big[u(c_t) + v(e_t)\big] \tag{16}$$

$$\text{s.t. } E_t\big[\beta b_{t+1} u'(c_{t+1})\big] \geq u'(c_t)(b_t - c_t) - e_t v'(e_t) \tag{17}$$

given b_0 and for $e_t = c_t + g_t$.

[14]Among others, Marcet and Marimon (1992) studied one-sided constraints in a small open economy, Broer (2013) characterized the stationary distribution of consumption, Ábrahám and Laczó (2018) characterized analytically the solution.

[15]See, among others, Alvarez and Jermann (2000), Kehoe and Perri (2002), Krueger, Lustig, and Perri (2008), and Ábrahám and Cárceles-Poveda (2010).

Unlike Example 1, the forward-looking constraint (17) involves one-period-ahead expectation; furthermore, the objective function is not present in the forward-looking constraints. Formally, this problem is a special case of $\mathbf{PP}_\mu$ for variables $s \equiv g$; $x \equiv b$, $a \equiv (c, b')$. Taking $h_0^0(x, a, s') \equiv u(c) + v(e)$ and $\mu = (1, 0)$ ensures that the objective function of $\mathbf{PP}_\mu$ coincides with (16). Letting $\ell(x, a, s') \equiv b'$, $h_0^1(x, a, s') \equiv bu'(c)$, $h_1^1(x, a, s') \equiv u'(c)(c - b) + ev'(e)$, and $N_1 = 0$ makes (17) a special case of (3) for $k = 0$ and $l = 1$. We can incorporate the objective function h_0^0 as part of a constraint by introducing h_1^0 arbitrarily large, ensuring that $\gamma_t^0 = 0$ so that $\mu_t^0 = 1$ for all t.

The objective function of the Lagrangian (5) becomes

$$\begin{aligned}\mathcal{L}_\mu(\boldsymbol{a}, \boldsymbol{\gamma}; x, s) \quad &= \mathrm{E}_0 \sum_{t=0}^{\infty} \beta^t \big[\mu_t^0\big(u(c_t) + v(e_t)\big) \\ &\quad + \mu_t^1 b_t u'(c_t) + \gamma_t^1\big[u'(c_t)(c_t - b_t) + e_t v'(e_t)\big]\big]. \end{aligned} \tag{18}$$

The **SPFE** takes the form

$$\begin{aligned} W(b, \mu, g) = \mathrm{SP} \inf_{\gamma^1 \geq 0} \sup_{c, b'} &\big\{\mu^0\big[u(c) + v(e)\big] + \mu^1 bu'(c) \\ &+ \gamma^1\big[u'(c)(c - b) + ev'(e)\big] + \beta \mathrm{E}\big[W\big(b', \mu', g'\big)|g\big]\big\} \\ &\text{s.t. } \mu^{0\prime} = \mu^0, \mu^{1\prime} = \gamma^1. \end{aligned}$$

The continuation problem $\mathbf{PP}_{\mu_1^*}$ is obtained by replacing the objective function in (16) with $E_1 \sum_{t=0}^{\infty} \beta^t [u(c_t) + v(e_t)] + \mu_1^{1,*} b_1^* u'(c_0)$ where $\mu_1^{1,*} = \gamma_0^{1,*}$ and for initial conditions (b_1^*, g_1). In this example, $\mu_t^{0,*} = 1$ for all t. Allowing for an arbitrary value, μ_0^0, as an argument of W guarantees its homogeneity of degree 1, with respect to μ, a property that we use in some of our theorems.

The key to finding numerical solutions to this problem is that the optimal policy satisfies $(c_t^*, b_t^*, \gamma_t^*) = \psi_W(b_t^*, \gamma_{t-1}^*, g_t)$ with initial conditions $(b_0^*, \gamma_{-1}^*) = (b_0, 0)$ for a time-invariant ψ_W that satisfies (17) and optimality conditions of the Ramsey problem.

Aiyagari et al. (2002) discussed how a near-unit root behavior of γ_t influences optimal debt and taxes and that debt acts as a buffer stock for adverse shocks. Faraglia, Marcet, Oikonomou, and Scott (2016) showed that the role of the co-state γ_t is to enforce a promised tax cut that, in equilibrium, lowers current interest rate costs for a government currently facing high deficits. Various papers exploit and extend the recursive formulation described here in models of Ramsey taxation.[16]

3. THE RELATIONSHIP BETWEEN $\mathbf{PP}_\mu$ AND THE **SPFE**

This section contains the main result of this paper, namely, that the maximization problem $\mathbf{PP}_\mu$ is equivalent to the **SPFE**, under fairly general conditions. In particular, we show *necessity*: solutions to $\mathbf{PP}_\mu$ are solutions to the *saddle-point functional equation* **SPFE** (Theorem 1). We also show that $\mathbf{PP}_{\mu_1^*}$ defines the continuation problem in our approach

[16]Among others: Faraglia, Marcet, Oikonomou, and Scott (2019) in a model where the government has to choose a portfolio of maturities; Marcet and Scott (2009) in a model with capital. Schmitt-Grohé and Uribe (2004) and Siu (2004) introduced nominal bonds and the role of monetary policy; Adam and Billi (2006) introduced a zero lower bound to interest rates.

(Proposition 1); this formalizes the discussion in Section 2.2.1. We also show *sufficiency*: if the **SPFE** value function W is differentiable in μ, then under minimal additional assumptions, its allocation-solution is a solution to $\mathbf{PP}_\mu$ (Theorem 2). We close the section showing that if the allocation-solution is unique, then W is differentiable in μ (Lemma 1) and that, in the absence of differentiability, a more general *Intertemporal Consistency Condition*, which is always satisfied when a solution to **SPFE** exists (Corollary to Theorem 2), ensures sufficiency. First, we lay out the different assumptions used to obtain these results.

3.1. *Assumptions About* $\mathbf{PP}_\mu$

We consider the following set of assumptions:

A1. s_t takes values from a set $S \subset R^K$. $\{s_t\}_{t=0}^\infty$ is a Markovian stochastic process defined on the probability space $(S_\infty, \mathcal{S}, P)$.

A2. (a) $X \subset R^n$ and A is a closed subset of R^m. (b) The functions $p : X \times A \times S \to R^q$ and $\ell : X \times A \times S \to X$ are continuous on (x, a) and, given (x, a), they are $\mathcal{S}$-measurable; furthermore, for any (x, s), the set $\{a \in A : p(x, a, s) \geq 0\}$ is bounded.

A3. For all (x, s), there is a program $\{\overline{a}_t\}_{t=0}^\infty$, with initial conditions (x, s), which satisfies constraints (2) and (3) for all $t \geq 0$.

A4. The functions $h_i^j : X \times A \times S \to R$, $i = 0, 1$, $j = 0, \ldots, l$, are uniformly bounded, continuous on (x, a) and, given (x, a), they are $\mathcal{S}$-measurable. Furthermore, $\beta \in (0, 1)$.

A5. The function $\ell(\cdot, \cdot, s)$ is linear and the function $p(\cdot, \cdot, s)$ is concave. X and A are convex sets.

A6. The functions $h_i^j(\cdot, \cdot, s)$, $i = 0, 1$, $j = 0, \ldots, l$, are concave.

A6s. In addition to **A6**, the functions $h_0^j(x, \cdot, s)$, $j = 0, \ldots, l$, are strictly concave.

A7. For all (x, s), and $j = 0, \ldots, l$, there exists a program[17] $\{\widetilde{a}_t\}_{t=0}^\infty$, with initial conditions (x, s), satisfying (2), such that $\mathrm{E}_0 \sum_{t=1}^{N_j+1} \beta^t h_0^j(\widetilde{x}_t, \widetilde{a}_t, s_t) + h_1^j(x, \widetilde{a}_0, s) > 0$ and, for $i \neq j$, $\mathrm{E}_0 \sum_{t=1}^{N_i+1} \beta^t h_0^i(\widetilde{x}_t, \widetilde{a}_t, s_t) + h_1^i(x, \widetilde{a}_0, s) \geq 0$.

A7s. In addition to **A7**, there is an $\epsilon > 0$ such that, for all (x, s), and $j = 0, \ldots, l$, the inequality in **A7** can be replaced by $\mathrm{E}_0 \sum_{t=1}^{N_j+1} \beta^t h_0^j(\widetilde{x}_t, \widetilde{a}_t, s_t) + h_1^j(x, \widetilde{a}_0, s) \geq \epsilon$.

Assumptions **A1–A3** are standard, they hold in most applications, and we treat them as our basic assumptions. Assumption **A4** guarantees bounded returns and does not preclude sustained growth of the endogenous state x (provided its growth rate is lower than β^{-1}).[18] Assumptions **A5–A6**—in particular, the concavity of the h_1^j functions[19]—are not satisfied in some models of interest; however, they are not used in our sufficiency results (e.g., Theorem 2). Assuming linearity of ℓ in Assumption **A5** is the natural consequence of decomposing the action, or control, a from the endogenous state x—which in many applications allows for a reduction of the dimension of the state space—while keeping convexity of the overall feasibility set.[20] Assumption **A7** is a standard interiority assumption (with **A6** , equivalent to the Slater condition), only needed to guarantee the existence

[17]We will refer to it as the j-interior program.

[18]Our theory can be extended to unbounded returns in the same way that standard dynamic programming can (see, e.g., Alvarez and Stokey (1998)). For simplicity, we focus here on the case of bounded returns.

[19]Note, however, that this assumption can be relaxed since what is needed is the convexity of the constraint set (3).

[20]More precisely, convexity of $\Gamma(\cdot, s, s')$, where $\Gamma(x, s, s') = \{x' : \exists a \in A \text{ s.t. } p(x, a, s) \geq 0 \text{ and } x' = \ell(x, a, s')\}$ (e.g., Stokey, Lucas, and Prescott (1989, Assumption 4.8)).

of Lagrange multipliers in R_+^{l+1} that guarantee the saddle-point, and Assumption **A7s** guarantees that the sequence of multipliers is uniformly bounded (Theorem 3).[21]

3.2. *The Recursive Formulation of* $\mathbf{PP}_\mu$ *(Necessity)*

We first show that, under certain standard assumptions, solutions to $\mathbf{PP}_\mu$ satisfy **SPFE**.

Given a value function W satisfying the **SPFE** (8) in any possible state $(x, \mu, s) \in X \times R_+^{l+1} \times S$, the corresponding *saddle-point policy correspondence* (*SP policy correspondence*) $\Psi_W : X \times R_+^{l+1} \times S \to A \times R_+^{l+1}$ (i.e., $\Psi_W(x, \mu, s)$ is a subset of $A \times R_+^{l+1}$) is

$$\begin{aligned}
&\Psi_W(x, \mu, s) \\
&\quad = \{(a^*, \gamma^*) \in A \times R_+^{l+1} \text{ satisfying } p(x, a^*, s) \geq 0 \\
&\qquad \text{s.t. } \mu h_0(x, a^*, s) + \gamma h_1(x, a^*, s) + \beta \mathrm{E}[W(\ell(x, a^*, s'), \varphi(\mu, \gamma), s')|s] \\
&\qquad \geq \mu h_0(x, a^*, s) + \gamma^* h_1(x, a^*, s) + \beta \mathrm{E}[W(\ell(x, a^*, s'), \varphi(\mu, \gamma^*), s')|s] \qquad (19) \\
&\qquad \geq \mu h_0(x, a, s) + \gamma^* h_1(x, a, s) + \beta \mathrm{E}[W(\ell(x, a, s'), \varphi(\mu, \gamma^*), s')|s] \qquad (20) \\
&\qquad \text{for all } (a, \gamma) \in A \times R_+^{l+1} \text{ satisfying } p(x, a, s) \geq 0\}.
\end{aligned}$$

The results below assume existence of a saddle-point $(\boldsymbol{a}^*, \gamma_0^*)$ of the Lagrangian that only accounts for the forward-looking constraint (3) of period zero. More precisely, $(\boldsymbol{a}^*, \gamma_0^*)$ is a solution to the following problem:

$$\begin{aligned}
\mathbf{SPP}_\mu: \quad SV(x, \mu, s) = \mathrm{SP} \inf_{\gamma \in R_+^{l+1}} \sup_{\{a_t\}_{t=0}^\infty} \Big\{ &\mu h_0(x_0, a_0, s_0) + \gamma h_1(x_0, a_0, s_0) \\
&+ \beta \mathrm{E}_0 \sum_{j=0}^{l} \varphi^j(\mu, \gamma) \sum_{t=0}^{N_j} \beta^t h_0^j(x_{t+1}, a_{t+1}, s_{t+1}) \Big\} \qquad (21)
\end{aligned}$$

$$\text{s.t. } x_{t+1} = \ell(x_t, a_t, s_{t+1}), \qquad p(x_t, a_t, s_t) \geq 0, \quad t \geq 0, \qquad (22)$$

$$\mathrm{E}_t \sum_{n=1}^{N_j+1} \beta^n h_0^j(x_{t+n}, a_{t+n}, s_{t+n}) + h_1^j(x_t, a_t, s_t) \geq 0, \quad j = 0, \ldots, l, t \geq 1, \qquad (23)$$

where (21) is obtained by adding the term $\gamma[\mathrm{E}_0 \sum_{t=0}^{N_j+1} \beta^t h_0^j(x_{t+1}, a_{t+1}, s_{t+1}) + h_1(x_0, a_0, s_0)]$ to the objective function of $\mathbf{PP}_\mu$ and rearranging. Note how (23) only holds for $t \geq 1$, that is, this Lagrangian only attaches a multiplier to the forward-looking constraint (3) at $t = 0$, while the remaining constraints (3) for $t > 0$ are kept as constraints; furthermore, $(\boldsymbol{a}^*, \gamma_0^*)$ solves $\mathbf{SPP}_\mu$ at (x, s) if, given $\gamma_0^* \in R_+^{l+1}$, the path $\boldsymbol{a}^*$ is maximal for (21) with respect to all the paths satisfying (22)–(23) and, given $\boldsymbol{a}^*$, γ_0^* is a minimal element for (21) in R_+^{l+1}.

The following theorem guarantees that the value function V_μ and the solution of $\mathbf{PP}_\mu$ satisfy **SPFE.**

[21]One can show that, for any (x, s), there exists a solution to $\mathbf{PP}_\mu$ if Assumptions **A1**–**A6** are satisfied (Proposition 1 in the 2011 version of this paper).

THEOREM 1—$\mathbf{PP}_\mu \Rightarrow \mathbf{SPFE}$: *Assume* **A1–A4**. *Assume, for any* $\mu \in R_+^{l+1}$ *and any initial condition* (x, s), *there is a saddle-point* $(\boldsymbol{a}^*, \gamma_0^*)$ *of* $\mathbf{SPP}_\mu$. *Then* $\boldsymbol{a}^*$ *solves* $\mathbf{PP}_\mu$, *the function* $W(x, \mu, s) \equiv V_\mu(x, s)$ *satisfies the* **SPFE** (8), *and* $(a_0^*, \gamma_0^*) \in \Psi_W(x, \mu, s)$.

PROOF: See Appendix B. *Q.E.D.*

This result assumes the existence of a saddle-point $(\boldsymbol{a}^*, \gamma_0^*)$ of the Lagrangian in $\mathbf{SPP}_\mu$. This assumption is a standard way to proceed in optimization theory; see, for example, Section 8.4 of Luenberger (1969). Existence can be checked directly in a given model for a solution obtained using a number of algorithms at hand that can solve $\mathbf{SPP}_\mu$ using our recursive formulation.

The existence of a saddle-point $(\boldsymbol{a}^*, \gamma_0^*)$ can be guaranteed if we strengthen the assumptions of Theorem 1 by requiring concavity and interiority; formally, we have the following.

COROLLARY TO THEOREM 1: *Assume* **A1–A6** *and* **A7** *and fix* $\mu \in R_+^{l+1}$. *Let* $\boldsymbol{a}^*$ *be a solution to* $\mathbf{PP}_\mu$ *with initial conditions* (x, s). *The function* $W(x, \mu, s) = V_\mu(x, s)$ *satisfies the* **SPFE** (8) *and there is a* $\gamma_0^* \in R_+^l$ *such that* $(a_0^*, \gamma_0^*) \in \Psi_W(x, \mu, s)$.

PROOF: See Appendix B. *Q.E.D.*

Note that the results of the corollary can be obtained from assumptions on the primitives. However, Theorem 1 holds more generally; for example, there are many problems where the feasible set of $\mathbf{PP}_\mu$ is not convex but its solution $\boldsymbol{a}^*$ has a saddle-point $(\boldsymbol{a}^*, \gamma_0^*)$ of $\mathbf{SPP}_\mu$ (e.g., in Example 2, functions h_0^1, h_1^1 may not satisfy Assumption **A6**; nevertheless, Theorem 1 applies).

The following result shows that $\mathbf{PP}_{\mu_1^*}$ is the appropriate continuation problem in our approach, formalizing our discussion in Section 2.2.1.

PROPOSITION 1—Continuation Problem: *Assume* **A1–A4**. *Fix* $\mu \in R_+^{l+1}$. *Assume that* $\mathbf{SPP}_\mu$ *has a saddle-point* $(\boldsymbol{a}^*, \gamma_0^*)$, *hence* $\boldsymbol{a}^*$ *solves* $\mathbf{PP}_\mu$. *Then, the continuation of this solution, namely,* $\{a_t^*\}_{t=1}^\infty$, *solves* $\mathbf{PP}_{\mu_1^*}$ *at* (x_1^*, s_1) *almost surely in* s_1, *where* $x_1^* = \ell(x, a_0^*, s_1)$ *and* $\mu_1^* = \varphi(\mu, \gamma_0^*)$.

PROOF: See Appendix B. *Q.E.D.*

Note that if $\boldsymbol{a}^*$ solves $\mathbf{PP}_\mu$ at (x, s) and $\mu_1^* \neq \mu$, then the solution of $\mathbf{PP}_\mu$ at (x_1^*, s_1) may differ from the continuation of $\boldsymbol{a}^*$. As explained in Section 2.2.1, in this case there is time-inconsistency.[22] The results in this section guarantee that even under time-inconsistency, the solution can be formulated recursively using the co-state μ_t^*.

A result analogous to the above corollary can be stated as follows: if Assumptions **A5–A6** and **A7** are also required, then the continuation of any solution to $\mathbf{PP}_\mu$ solves $\mathbf{PP}_{\mu_1^*}$.

3.3. *The Sufficiency of* SPFE

We now turn to our sufficiency theorem: $\mathbf{SPFE} \Rightarrow \mathbf{PP}_\mu$, where the value function W, satisfying the **SPFE** (8), is assumed to be continuous in (x, μ) and convex and homogeneous of degree 1 in μ, for every s, properties which are satisfied by the Lagrangian

[22]Strictly speaking, time-inconsistency arises generically if there is no scalar ξ such that $\mu = \xi\mu_1^*$.

$\mathcal{L}_\mu$—as a function of (x, μ)—associated with the value function V_μ of $\mathbf{PP}_\mu$. We obtain this result assuming that W is also differentiable in μ, a property that is satisfied when the solution $\mathbf{a}^*$ generated by Ψ_W is unique (Lemma 1). In the next subsection, we dispense with this assumption and replace it with a weaker *intertemporal consistency condition* (**ICC**), which is satisfied when W is differentiable in μ: the intertemporal Euler equation with respect to μ must be satisfied. We also show that when **SPFE** has a solution—possibly not unique—there is always a solution satisfying **ICC** (Corollary to Theorem 2).

THEOREM 2—**SPFE** $\Rightarrow$ $\mathbf{PP}_\mu$: *Assume* **A4** *and that* W, *satisfying the* **SPFE**, *is continuous in* (x, μ) *and convex*, *homogeneous of degree* 1, *and differentiable in* μ, *for every* s. *Let* Ψ_W *be* the SP policy correspondence *associated with* W *which generates a solution* $(\mathbf{a}^*, \boldsymbol{\gamma}^*)_{(x,\mu,s)}$ *satisfying* $\lim_{t\to\infty} \beta^t W(x_t^*, \mu_t^*, s_t) = 0$; *then* $\mathbf{a}^*$ *is a solution to* $\mathbf{PP}_\mu$ *at* (x, s), *and* $V_\mu(x, s) = W(x, \mu, s)$.

As a theorem of sufficiency, the main assumption is the existence of a saddle-point Bellman equation (**SPFE**) with its corresponding solution, but the assumptions on the h_i^j functions are minimal—in particular, we assume boundedness (**A4**) but not concavity—and with respect to W, the only "stringent" assumption is its differentiability with respect to μ, an assumption which—as Lemma 1 shows—is satisfied if the solution $\mathbf{a}^*$ is unique, as it is the case when W is concave and the h_0^j functions strictly concave in x (i.e., Assumption **A6s**).[23]

PROOF OF THEOREM 2: The proof is divided into two parts. Part I shows that when W satisfies **SPFE** (8), then the forward-looking constraints of $\mathbf{PP}_\mu$ are satisfied and W takes the form of the objective function of $\mathbf{PP}_\mu$. Part II shows that $\mathbf{a}^*$ is a maximal element of $\mathbf{PP}_\mu$ and, therefore, that $V_\mu(x, s) = W(x, \mu, s)$ (see Appendix B). The differentiability assumption is only used in Part I.

Part I: Note that if W is homogeneous of degree 1 and differentiable in μ, then, by Euler's theorem, it has a unique representation $W(x, \mu, s) = \sum_{j=0}^{l} \mu^j \omega^j(x, \mu, s)$, where ω^j is the partial derivative of W with respect to μ^j. Given this *Euler representation*, the minimality condition (19) takes the form

$$\begin{aligned}
&\mu h_0(x, a^*, s) + \gamma h_1(x, a^*, s) + \beta \mathrm{E}\big[\varphi(\mu, \gamma)\omega\big(\ell(x, a^*, s'), \varphi(\mu, \gamma^*), s'\big)|s\big] \\
&\quad \geq \mu h_0(x, a^*, s) + \gamma^* h_1(x, a^*, s) \\
&\qquad + \beta \mathrm{E}\big[\varphi(\mu, \gamma^*)\omega\big(\ell(x, a^*, s'), \varphi(\mu, \gamma^*), s'\big)|s\big],
\end{aligned} \tag{24}$$

and, by convexity of W in μ, it is satisfied if and only if the following *Kuhn–Tucker* conditions are satisfied:[24]

$$h_1^j(x, a^*, s) + \beta \mathrm{E}\big[\omega^j\big(x^{*\prime}, \varphi(\mu, \gamma^*), s'\big)|s\big] \geq 0, \tag{25}$$

$$\gamma^{*j}\big[h_1^j(x, a^*, s) + \beta \mathrm{E}\big[\omega^j\big(x^{*\prime}, \varphi(\mu, \gamma^*), s'\big)|s\big]\big] = 0. \tag{26}$$

[23]See, for example, Theorem 4.8 in Stokey, Lucas, and Prescott (1989).

[24]Note that in the left-hand side of (24), we have $\omega(\ell(x, a^*, s'), \varphi(\mu, \gamma^*), s')$ instead of $\omega(\ell(x, a^*, s'), \varphi(\mu, \gamma), s')$. This follows from the fact that (24) and (19) have the same Kuhn–Tucker conditions (25) and (26); see Fact F4, Lemma 4A in Appendix C.

Alternatively, in order to obtain a Euler equation for the intertemporal minimization problem, the minimality condition (24) can also be written as a choice of μ': for $j = 0, \dots, k$, $\mu'^j \geq \mu^j$ (i.e., $\mu'^j - \mu^j = \gamma^j \geq 0$) and for $j = k+1, \dots, l$, $\mu'^j \geq 0$ (i.e., $\mu'^j = \gamma^j \geq 0$), in which case the envelope theorem, with respect to μ, takes the form

$$\partial_{\mu^j} W(x^*, \mu^*, s) = \omega^j(x^*, \mu^*, s) = \begin{cases} h_0^j(x^*, a^*, s) - h_1^j(x^*, a^*, s) + \lambda^{j*} & \text{if } j = 0, \dots, k, \\ h_0^j(x^*, a^*, s) & \text{if } j = k+1, \dots, l, \end{cases} \tag{27}$$

where λ^{j*} is the Lagrange multiplier for the constraint $\mu'^{j*} - \mu^{j*} \geq 0$. Therefore, for $j = k+1, \dots, l$, $\omega^j(x^*, \mu^*, s)$ is already defined and, for $j = 0, \dots, k$, we use the first-order condition with respect to μ'^j, to obtain

$$h_1^j(x^*, a^*, s) + \beta \mathrm{E}\big[\omega^j(x'^*, \mu'^*, s_1'|s\big] - \lambda^{j*} = 0. \tag{28}$$

Substituting (28) into (27) results in

$$\omega^j(x^*, \mu^*, s) = \begin{cases} h_0^j(x^*, a^*, s) + \beta \mathrm{E}\big[\omega^j(x'^*, \mu'^*, s')|s\big] & \text{if } j = 0, \dots, k, \\ h_0^j(x^*, a^*, s) & \text{if } j = k+1, \dots, l. \end{cases} \tag{29}$$

Note that, for $j = 0, \dots, k$, the equation is the intertemporal Euler equation—that is, in our approach it is a result of the dynamic optimization problem, while in the "promised-utility" approach it is a constraint: the "promise-keeping" constraint.

The boundedness assumption **A4**, together with (25) and $\lim_{t\to\infty} \beta^t W(x_t^*, \mu_t^*, s_t) = 0$, imply that $\lim_{t\to\infty} \beta^t \omega^j(x_t^*, \mu_t^*, s_t) = 0$, for $j = 0, \dots, k$. Therefore, we can iterate (29) and obtain

$$\omega^j(x_t^*, \mu_t^*, s_t) = \mathrm{E}_t \sum_{n=0}^{N_j} \beta^n h_0^j(x_{t+n}^*, a_{t+n}^*, s_{t+n}). \tag{30}$$

Equation (30) has two implications. First, it shows that the *Kuhn–Tucker* conditions (25) can be expressed as

$$h_1^j(x_t^*, a_t^*, s_t) + \beta \mathrm{E} \sum_{n=0}^{N_j} \big[\beta^n h_0^j(x_{t+n+1}^*, a_{t+n+1}^*, s_{t+n+1})|s_t\big] \geq 0, \quad \text{for } j = 0, \dots, l \text{ and } t \geq 0;$$

in other words, that when W is differentiable in μ, solutions to **SPFE** satisfy the forward-looking constraints of $\mathbf{PP}_\mu$. Second, it shows that the unique Euler representation of W at (x, μ, s) is

$$W(x, \mu, s) = \sum_{j=0}^{l} \mu^j \omega^j(x, \mu, s) = \mathrm{E}\left[\sum_{j=0}^{l} \sum_{t=0}^{N_j} \beta^n \mu^j h_0^j(x_t^*, a_t^*, s_t)|s\right], \tag{31}$$

with $(x_0^*, s_0) = (x, s)$. That is, W takes the form of the objective function of $\mathbf{PP}_\mu$. These are the two results we wanted to obtain in Part I. *Q.E.D.*

Uniqueness and Sufficiency Without Differentiability of W with respect to μ

If W satisfies **SPFE,** for any (x, s), the function $W(x, \cdot, s) : R_+^{l+1} \to R$ is finite and, we assume, it is continuous and convex, therefore it is *almost surely* differentiable—that is, for almost any $\mu \in R_+^{l+1}$, it is differentiable (1970 (1970, Theorem 25.5)). However, W is an endogenous function and, in particular, at (x_t^*, μ_t^*, s_t) the value function W may be non-differentiable with probability 1 since (x_t^*, μ_t^*) is an endogenous choice; in other words, while non-differentiability with respect to μ may not be an issue "at the start", it can be a problem "along a solution path". Furthermore, differentiability of W may not be an easy condition to check. To analyze these issues and to obtain sufficiency results **(SPFE** $\Rightarrow$ $\mathbf{PP}_\mu$), when W is not necessarily differntiable, we use subdifferential calculus.[25]

Let $\partial_\mu W(x, \mu, s)$ denote the *subdifferential* of W at (x, μ, s) with respect to μ—that is,

$$\partial_\mu W(x, \mu, s) = \left\{\omega \in R^{l+1} \mid W(x, \widetilde{\mu}, s) \geq W(x, \mu, s) + (\widetilde{\mu} - \mu)\omega \text{ for all } \widetilde{\mu} \in R_+^{l+1}\right\}.$$

For any $\omega(x, \mu, s) \in \partial_\mu W(x, \mu, s)$, W has a Euler representation $W(x, \mu, s) = \mu\omega(x, \mu, s)$. We call $\omega(x, \mu, s)$ a *Euler representation selection.* In particular, if $\omega_t(x_t^*, \mu_t^*, s_t) \in \partial_\mu W(x_t^*, \mu_t^*, s_t)$, there are selections $\omega_t(x_{t+1}^*, \varphi(\mu_t^*, \gamma_t^*), s_{t+1}) \in \partial_\mu W(x_{t+1}^*, \varphi(\mu_t^*, \gamma_t^*), s_{t+1})$—for every s_{t+1}, following s_t—satisfying

$$\begin{aligned}
&\mu\omega_t(x_t^*, \mu_t^*, s_t) \\
&\quad = \mu h_0(x_t^*, a_t^*, s_t) + \gamma_t^* h_1(x_t^*, a_t^*, s_t) \\
&\qquad + \beta \mathrm{E}\big[\varphi(\mu_t^*, \gamma_t^*)\omega_t(\ell(x_t^*, a_t^*, s_{t+1}), \varphi(\mu_t^*, \gamma_t^*), s_{t+1})|s_t\big] \\
&\quad \leq \mu h_0(x_t^*, a_t^*, s_t) + \gamma h_1(x_t^*, a_t^*, s_t) \\
&\qquad + \beta \mathrm{E}\big[\varphi(\mu_t^*, \gamma)\omega_t(\ell(x_t^*, a_t^*, s_{t+1}), \varphi(\mu_t^*, \gamma_t^*), s_{t+1})|s_t\big],
\end{aligned} \tag{32}$$

for all $\gamma \in R_+^{l+1}$, and a^* is a maximal element in the corresponding saddle-point problem (i.e., given the selections and γ^*). Furthermore, the corresponding Kuhn–Tucker (complementary slackness) conditions

$$h_1^j(x_t^*, a_t^*, s_t) + \beta \mathrm{E}\big[\omega_t^j(x_{t+1}^*, \mu_{t+1}^*, s_{t+1})|s_t\big] \geq 0, \tag{33}$$

$$\gamma_t^{*j}\big[h_1^j(x, a_t^*, s_t) + \beta \mathrm{E}\big[\omega_t^j(x_{t+1}^*, \mu_{t+1}^*, s_{t+1})|s_t\big]\big] = 0, \tag{34}$$

are necessary and sufficient for (32) to be satisfied (Lemma 5A in Appendix C).

The subindex t in $\omega_t(x_t^*, \mu_t^*, s_t) \in \partial_\mu W(x_t^*, \mu_t^*, s_t)$ denotes that the *Euler representation selection* is made at (x_t^*, μ_t^*, s_t) and $\omega_t(x_{t+1}^*, \varphi(\mu_t^*, \gamma_t^*), s_{t+1})$ denotes a contingent selection of $\partial_\mu W(x_{t+1}^*, \varphi(\mu_t^*, \gamma_t^*), s_{t+1})$ made at (x_t^*, μ_t^*, s_t), while choosing a_t^*.

The value $W(x, \mu, s)$ is independent of its Euler representations; in particular, $\mu_{t+1}^* \times \omega_{t+1}(x_{t+1}^*, \mu_{t+1}^*, s_{t+1}) = \mu_{t+1}^*\omega_t(x_{t+1}^*, \mu_{t+1}^*, s_{t+1})$. However, for $j = 0, \dots, k$, it may be the case that $\omega_{t+1}^j(x_{t+1}^*, \mu_{t+1}^*, s_{t+1}) \neq \omega_t^j(x_{t+1}^*, \mu_{t+1}^*, s_{t+1})$; in other words, the selection of $\partial_\mu W(x_{t+1}^*, \mu_{t+1}^*, s_{t+1})$ made at $(x_{t+1}^*, \mu_{t+1}^*, s_{t+1})$ may be *inconsistent* with the contingent selection made at (x_t^*, μ_t^*, s_t), which can only happen if $\partial_\mu W(x_{t+1}^*, \mu_{t+1}^*, s_{t+1})$ is not a singleton (i.e., if W is not differentiable, with respect to μ, at μ_{t+1}^*), resulting in multiple saddle-point solutions. In fact, this *inconsistency* is the problem that may arise when W is

[25]See Appendix C for definitions and supporting results.

not differentiable. For instance, Messner and Pavoni's (2004) example relies on this inconsistency to show that there are cases where solutions to **SPFE** are not solutions to $\mathbf{PP}_\mu$. We now discuss three different conditions guaranteeing that such an inconsistency problem does not arise. However, before we can state these conditions, we need to develop more our results.

Our starting point is the Euler representation (31), which we have derived in the proof of Theorem 2 (Part I) using the Kuhn–Tucker conditions (25) and differentiability (the envelope theorem). In fact, we have derived (30)—the key result to show that the forward-looking constraints of $\mathbf{PP}_\mu$ are satisfied—to obtain (31). But, as we now show, the latter can be satisfied even when W is not differentiable in μ. To see this, first note that, by (34), the value function has the following recursive representation:

$$\begin{aligned}
W(x_t^*, \mu_t^*, s_t) &= \mu_t^* \omega_t(x_t^*, \mu_t^*, s_t) \\
&= \mu_t^* h_0(x_t^*, a_t^*, s_t) + \gamma_t^* h_1(x_t^*, a_t^*, s_t) + \beta \mathrm{E}\big[W\big(x_{t+1}^*, \varphi(\mu_t^*, \gamma_t^*), s_{t+1}\big)|s_t\big] \\
&= \mu_t^* h_0(x_t^*, a_t^*, s_t) + \gamma_t^* h_1(x_t^*, a_t^*, s_t) \\
&\quad + \beta \mathrm{E}\big[\varphi(\mu_t^*, \gamma_t^*)\omega_t\big(x_{t+1}^*, \varphi(\mu_t^*, \gamma_t^*), s_{t+1}\big)|s_t\big] \\
&= \mu_t^* h_0(x_t^*, a_t^*, s_t) + \beta \sum_{j=0}^{k} \mu_t^{*j} \mathrm{E}\big[\omega_t^j\big(x_{t+1}^*, \varphi(\mu_t^*, \gamma_t^*), s_{t+1}\big)|s_t\big] \\
&\quad + \gamma_t^*\big[h_1(x_t^*, a_t^*, s_t) + \beta \mathrm{E}\omega_t\big(x_{t+1}^*, \varphi(\mu_t^*, \gamma_t^*), s_{t+1}\big)|s_t\big] \\
&= \mu_t^* h_0(x_t^*, a_t^*, s_t) + \beta \sum_{j=0}^{k} \mu_t^{*j} \mathrm{E}\big[\omega_t^j\big(x_{t+1}^*, \varphi(\mu_t^*, \gamma_t^*), s_{t+1}\big)|s_t\big];
\end{aligned} \tag{35}$$

however, to have (30), a more strict recursive representation is needed (note the change of subindex on the right-hand side ω):

$$\mu_t^* \omega_t(x_t^*, \mu_t^*, s_t) = \mu_t^* h_0(x_t^*, a_t^*, s_t) + \beta \sum_{j=0}^{k} \mu_t^{*j} \mathrm{E}\big[\omega_{t+1}^j\big(x_{t+1}^*, \varphi(\mu_t^*, \gamma_t^*), s_{t+1}\big)|s_t\big].$$

To obtain this representation, we need to be more explicit about the fact that solutions $(\mathbf{a}^*, \boldsymbol{\gamma}^*)_{(x,\mu,s)}$ generated by Ψ_W are given by *saddle-point policy selections* ψ_W^s of Ψ_W. In particular, among all solutions, it is always possible to choose one where the selection is fixed from the beginning: at (x, μ, s). In other words, one needs to make these choices along the solution path, $(a_t^*, \gamma_t^*) = \psi_W^s(x_t^*, \mu_t^*, s_t)$, where ψ_W^s is the original selection given by $\psi_W^s(x, \mu, s) \in \Psi_W(x, \mu, s)$ and satisfies $\lim_{t\to\infty} \beta^t W(x_t^*, \mu_t^*, s_t) = 0$. Given this saddle-point policy selection, we now sequentially unfold the saddle-point value function W, say from (x_t^*, μ_t^*, s_t):[26]

$$\begin{aligned}
&\mu_t^* \omega_t(x_t^*, \mu_t^*, s_t) \\
&\quad = \mu_t^* h_0(x_t^*, a_t^*, s_t) + \gamma_t^* h_1(x_t^*, a_t^*, s_t) + \beta \mathrm{E}\big[W\big(x_{t+1}^*, \varphi(\mu_t^*, \gamma_t^*), s_{t+1}\big)|s_t\big]
\end{aligned}$$

[26]To simplify our expressions, we introduce a new notation: given $x \in R^{l+1}$, let $I^k x^j = x^j$ if $j = 0, \dots, k$ and $I^k x^j = 0$ if $j = k+1, \dots, l$.

$$
\begin{aligned}
&= \mu_t^* h_0(x_t^*, a_t^*, s_t) + \gamma_t^* h_1(x_t^*, a_t^*, s_t) \\
&\quad + \beta \mathrm{E}\big[\mu_{t+1}^* h_0(x_{t+1}^*, a_{t+1}^*, s_{t+1}) + \gamma_{t+1}^* h_1(x_{t+1}^*, a_{t+1}^*, s_{t+1}) \\
&\quad + \beta \mathrm{E}\big[W(x_{t+2}^*, \varphi(\mu_{t+1}^*, \gamma_{t+1}^*), s_{t+2})|s_{t+1}\big]|s_t\big] \\
&= \mu_t^*\big[h_0(x_t^*, a_t^*, s_t) + \beta \mathrm{E}\big[I^k h_0(x_{t+1}^*, a_{t+1}^*, s_{t+1})|s_t\big]\big] \\
&\quad + \gamma_t^*\big[h_1(x_t^*, a_t^*, s_t) + \beta \mathrm{E}\big[h_0(x_{t+1}^*, a_{t+1}^*, s_{t+1})|s_t\big]\big] \\
&\quad + \beta \mathrm{E}\big[\gamma_{t+1}^* h_1(x_{t+1}^*, a_{t+1}^*, s_{t+1}) + \beta \mathrm{E}\big[W(x_{t+2}^*, \varphi(\mu_{t+1}^*, \gamma_{t+1}^*), s_{t+2})|s_{t+1}\big]|s_t\big] \\
&= \mu_t^*\big[h_0(x_t^*, a_t^*, s_t) + \beta \mathrm{E}\big[I^k h_0(x_{t+1}^*, a_{t+1}^*, s_{t+1}) + \beta I^k h_0(x_{t+2}^*, a_{t+2}^*, s_{t+2})|s_t\big]\big] \\
&\quad + \gamma_t^*\big[h_1(x_t^*, a_t^*, s_t) + \beta \mathrm{E}\big[h_0(x_{t+1}^*, a_{t+1}^*, s_{t+1}) + \beta h_0(x_{t+2}^*, a_{t+2}^*, s_{t+2})|s_{t+1}\big]s_t\big] \\
&\quad + \beta \mathrm{E}\big[\gamma_{t+1}^*\big[h_1(x_{t+1}^*, a_{t+1}^*, s_{t+1}) + \beta h_0(x_{t+2}^*, a_{t+2}^*, s_{t+2})\big]s_{t+1}|s_t\big] \\
&\quad + \beta^2 \mathrm{E}\big[W(x_{t+2}^*, \varphi(\mu_{t+1}^*, \gamma_{t+1}^*), s_{t+2}|s_t\big] \\
&\quad \ldots \\
&= \mu_t^*\left[h_0(x_t^*, a_t^*, s_t) + \beta \mathrm{E}\left[I^k \sum_{n=0}^{T} \beta^n h_0(x_{t+1+n}^*, a_{t+1+n}^*, s_{t+1+n})|s_t\right]\right] \\
&\quad + \gamma_t^*\left[h_1(x_t^*, a_t^*, s_t) + \beta \mathrm{E}\left[h_0(x_{t+1}^*, a_{t+1}^*, s_{t+1})\right.\right. \\
&\quad \left.\left. + \beta I^k \sum_{n=0}^{T-1} \beta^n h_0(x_{t+2+n}^*, a_{t+2+n}^*, s_{t+2+n})|s_t\right]\right] \\
&\quad + \beta \mathrm{E}\left[\gamma_{t+1}^*\left[h_1(x_{t+1}^*, a_{t+1}^*, s_{t+1})\right.\right. \\
&\quad \left.\left. + \beta \mathrm{E}\left[h_0(x_{t+2}^*, a_{t+2}^*, s_{t+2}) + \beta I^k \sum_{n=0}^{T-2} \beta^n h_0(x_{t+3+n}^*, a_{t+3+n}^*, s_{t+3+n})|s_{t+1}\right]\right]\middle|s_t\right] \\
&\quad \ldots \\
&\quad + \beta^T \mathrm{E}\big[\gamma_{t+T}^*\big[h_1(x_{t+T}^*, a_{t+T}^*, s_{t+T}) + \beta h_0(x_{t+T+1}^*, a_{t+T+1}^*, s_{t+T+1})\big]s_{t+T}|s_t\big] \\
&\quad + \beta^{T+1} \mathrm{E}\big[W(x_{t+T+1}^*, \varphi(\mu_{t+T}^*, \gamma_{t+T}^*), s_{t+T+1})|s_{t+T}|s_t\big].
\end{aligned}
$$

Note that, by our boundedness assumption (**A4**), the terms in brackets multiplying the Lagrange multipliers converge, as $T \to \infty$; say, for γ_{t+m}^* to

$$
\begin{aligned}
&\left[h_1(x_{t+m}^*, a_{t+m}^*, s_{t+m}) + \beta \mathrm{E}\left[h_0(x_{t+m+1}^*, a_{t+m+1}^*, s_{t+m+1})\right.\right. \\
&\qquad \left.\left. + \beta I^k \sum_{n=0}^{\infty} \beta^n h_0(x_{t+m+2+n}^*, a_{t+m+2+n}^*, s_{t+m+2+n})|s_{t+m}\right]\right].
\end{aligned}
$$

But given that the saddle-point policy selection ψ_W^s is the same in all iterations, the term in the inner bracket is just $\omega_{t+m}(x^*_{t+m+1}, \mu^*_{t+m+1}, s_{t+m+1})$. Therefore, as $T \to \infty$,

$$\begin{aligned}
&\mu_t^* \omega_t(x_t^*, \mu_t^*, s_t) \\
&= \mathrm{E}\left[\sum_{j=0}^{l}\sum_{n=0}^{N_j} \beta^n \mu_t^{*j} h_0^j(x^*_{t+n}, a^*_{t+n}, s_{t+n})|s_t\right] \\
&\quad + \gamma_t^*\left[h_1(x_t^*, a_t^*, s_t) + \beta \mathrm{E}\left[\omega_t(x^*_{t+1}, \mu^*_{t+1}, s_{t+1})|s_t\right]\right] \\
&\quad + \beta \mathrm{E}\left[\gamma^*_{t+1}\left[h_1(x^*_{t+1}, a^*_{t+1}, s_{t+1}) + \beta \mathrm{E}\left[\omega_{t+1}(x^*_{t+2}, \mu^*_{t+2}, s_{t+2})|s_{t+1}\right]\right]|s_t\right] \\
&\quad \cdots \\
&= \mathrm{E}\left[\sum_{j=0}^{l}\sum_{n=0}^{N_j} \beta^n \mu_t^{*j} h_0^j(x^*_{t+n}, a^*_{t+n}, s_{t+n})|s_t\right],
\end{aligned}$$

where the last equality follows from the "slackness condition" (34). In sum, we have obtained (31) and, in particular, that $\omega^j_{t+1}(x^*_{t+1}, \mu^*_{t+1}, s_{t+1}) = \omega^j_t(x^*_{t+1}, \mu^*_{t+1}, s_{t+1}) \equiv \omega^j(x^*_{t+1}, \mu^*_{t+1}, s_{t+1})$. This derivation of (31) has two implications, which correspond to the first two conditions that guarantee that inconsistency problems do not arise.

First, the role of *uniqueness*. If $\mathbf{a}^*$ is unique, then, by (31), the Euler representation is unique.[27] However, since the *subdifferential* of W is composed of Euler representation selections, this means that $\partial_\mu W$ is a singleton and, therefore, more formally, we have the following:

LEMMA 1: *If W, satisfying the* **SPFE**, *is continuous in (x, μ) and convex in μ, for every s, and for $(\mathbf{a}^*, \boldsymbol{\gamma}^*)_{(x,\mu,s)} \in \Psi_W(x, \mu, s)$ $\mathbf{a}^*$ is unique, then W is differentiable in μ at (x, μ, s).*

In fact, what Lemma 1 says is that "uniqueness" is not a new condition with respect to Theorem 2, but a relatively simple condition to check, which guarantees differentiability.

Second, the role of *fixing the saddle-point policy selection*. What our derivation of (31) shows is that if, as it is usually done in computations, the saddle-point policy selection is the same in the sequential iterations of **SPFE**, the forward-looking constraints are consistently defined and, therefore, (30) is satisfied.[28] However, if, at (x_t^*, μ_t^*, s_t), W is not differentiable in μ and **SPFE** is restarted with a different saddle-point policy selection, say, $\psi_W^{\tilde{s}}$, then, for some j, $\tilde{\omega}_t^j(x_t^*, \mu_t^*, s_t) \neq \omega^j_{t-1}(x_t^*, \mu_t^*, s_t)$, and the resulting solution—up to t with ψ_W^s and from t with $\psi_W^{\tilde{s}}$—may not be a solution to $\mathbf{PP}_\mu$ at (x, s).

Therefore, there is a need to provide a condition (our "third") guaranteeing consistency that can be checked.

ICC. A solution $(\mathbf{a}^*, \boldsymbol{\gamma}^*)_{(x,\mu,s)}$ generated by the SP policy correspondence Ψ_W associated with W satisfies the *Intertemporal Consistency Condition* if, for $t \geq 0$ and $j = 0, \ldots, k$, its *Euler representation selections* satisfy the intertemporal Euler equation (29); that is,

[27]Note that if, in addition, $\boldsymbol{\gamma}^*$ is also unique, then there is a unique saddle-point policy selection ψ_W^s, that is, the saddle-point policy function ψ_W.

[28]In the derivation of (31), by keeping the same selection, we had, for $j = 0, \ldots, k$ and $t > 0$, $\omega^j_{t+1}(x^*_{t+1}, \mu^*_{t+1}, s_{t+1}) = \omega^j_t(x^*_{t+1}, \mu^*_{t+1}, s_{t+1})$.

if

$$\omega^j(x_t^*, \mu_t^*, s_t) = h_0^j(x^*, a_t^*, s) + \beta \mathrm{E}[\omega^j(x_{t+1}^*, \mu_{t+1}^*, s_{t+1})|s_t].$$

COROLLARY TO THEOREM 2: *Assume* **A4** *and that W, satisfying the* **SPFE**, *is continuous in (x, μ) and convex and homogeneous of degree 1 in μ, for every s. Let Ψ_W be the SP policy correspondence associated with W, which generates solutions $(\mathbf{a}^*, \boldsymbol{\gamma}^*)_{(x,\mu,s)}$, satisfying $\lim_{t\to\infty} \beta^t W(x_t^*, \mu_t^*, s_t) = 0$. If a solution also satisfies the* **ICC**, *then* $\mathbf{a}^*$ *is a solution to* $\mathbf{PP}_\mu$ *at (x, s), and $V_\mu(x, s) = W(x, \mu, s)$. Furthermore, there is a solution which satisfies the **ICC**.*

The previous discussion provides the proof to this corollary, since the only missing piece of the proof of Theorem 2, if differentiability of W in μ is not assumed, is the *Euler equation* (30), which is provided by **ICC**, and we have also shown how to obtain a solution that satisfies **ICC**, provided that **SPFE** has a solution. Nevertheless, we have not provided a recursive algorithm that guarantees the Euler equation (30) is satisfied. This can be found in Marimon and Werner (2019), who also provided a more comprehensive discussion of the inconsistency issues discussed here, based on their envelope theorem without differentiability which, in our context, generalizes (27).

4. EXISTENCE OF SADDLE-POINT VALUE FUNCTIONS

In this section, we address the issue of the existence of value functions satisfying the **SPFE** (Theorem 3(i)). The existence of saddle-points is needed to show that there is a well-defined contraction mapping generalizing the *contraction mapping theorem* to a *dynamic saddle-point problem* corresponding to the **SPFE** (Theorem 3(iii)).

We first define the space of bounded value functions (in x) which are convex and homogeneous of degree 1 (in μ):

$$\begin{aligned}\mathcal{M}_b = \{W : X \times R_+^{l+1} \times S \to R \\ &\text{(i) } W(\cdot, \cdot, s) \text{ is continuous, } W(\cdot, \mu, s) \text{ is bounded when } \|\mu\| \le 1, \\ &\text{and } W(x, \mu, \cdot) \text{ is } \mathcal{S}\text{-measurable,} \\ &\text{(ii) } W(x, \cdot, s) \text{ is convex and homogeneous of degree } 1\},\end{aligned}$$

and we also define its subspace of concave functions (in x): $\mathcal{M}_{bc} = \{W \in \mathcal{M}_b$ and (iii) $W(\cdot, \mu, s)$ is concave$\}$. Both spaces are normed vector spaces with the norm

$$\|W\| = \sup\{|W(x, \mu, s)| : \|\mu\| \le 1, x \in X, s \in S\}.$$

We show in Appendix D (Lemma 8A) that these are complete metric spaces and, therefore, suitable spaces for the *contraction mapping theorem.* Note that $V_\mu(x, s)$, the value of $\mathbf{PP}_\mu$ with initial conditions (x, s), can also be represented as a function $V_.(\cdot, \cdot)$—at (x, μ, s)—which is in $\mathcal{M}_b$ whenever Assumptions **A2–A4** are satisfied, and in $\mathcal{M}_{bc}$ if, in addition, Assumptions **A5–A6** are satisfied (See Lemma 1A in Appendix B.).

Let $\mathcal{M}$ denote either $\mathcal{M}_b$ or $\mathcal{M}_{bc}$. Then the **SPFE** defines a saddle-point operator $T^* : \mathcal{M} \longrightarrow \mathcal{M}$ given by

$$\begin{aligned}(T^*W)(x, \mu, s) = \ & \mathrm{SP} \min_{\gamma \ge 0} \max_a \{\mu h_0(x, a, s) + \gamma h_1(x, a, s) + \beta \mathrm{E}[W(x', \mu', s')|s]\} \\ & \text{s.t. } x' = \ell(x, a, s'), \qquad p(x, a, s) \ge 0, \\ & \text{and} \quad \mu' = \varphi(\mu, \gamma). \end{aligned} \tag{36}$$

In defining T^* as a *saddle-point operator*, we have implicitly assumed that there is a saddle-point (a^*, γ^*) satisfying

$$\begin{aligned}
&\mu h_0(x, a^*, s) + \gamma h_1(x, a^*, s) + \beta \mathrm{E}\big[W(x^{*\prime}, \mu', s')|s\big] \\
&\quad \geq \mu h_0(x, a^*, s) + \gamma^* h_1(x, a^*, s) + \beta \mathrm{E}\big[W(x^{*\prime}, \mu^{*\prime}, s')|s\big] \\
&\quad \geq \mu h_0(x, a, s) + \gamma^* h_1(x, a, s) + \beta \mathrm{E}\big[W(x', \mu^{*\prime}, s')|s\big], \\
&\qquad \forall \gamma \in \mathcal{R}_+^{l+1}, \mu' = \varphi(\mu, \gamma) \text{ and } a \text{ with } p(x, a, s) \geq 0, x' = \ell(x, a, s').
\end{aligned}$$

To guarantee that the T^* operator preserves measurability, we strengthen Assumption **A1**:

A1b. s_t takes values from a compact and convex set $S \subset R^K$. $\{s_t\}_{t=0}^{\infty}$ is a Markovian stochastic process defined on the probability space $(S_\infty, \mathcal{S}, P)$ with transition function Q on $(S, \mathcal{S})$ satisfying the Feller property.[29]

As we have seen in Section 3, any $W \in \mathcal{M}$ has a—possibly non-unique—*Euler representation* $W(x, \mu, s) = \mu\omega(x, \mu, s)$ (see also Appendix C). Furthermore, with this representation, (a^*, γ^*) is a saddle-point of **SPFE** if, and only if, it is a saddle-point of the Lagrangian

$$\begin{aligned}
\mathcal{L}(a, \gamma; (x, \mu, s)) = \mu\Bigg[h_0(x, a, s) + \beta \mathrm{E}\Bigg[\sum_{j=0}^{k} \omega^j(x', \mu', s')|s\Bigg]\Bigg] \\
+ \gamma\big[h_1(x, a, s) + \beta \mathrm{E}\big[\omega(x', \mu', s')|s\big]\big], \\
\forall \gamma \in \mathcal{R}_+^{l+1}, \mu' = \varphi(\mu, \gamma) \text{ and } a \text{ with } p(x, a, s) \geq 0, x' = \ell(x, a, s').
\end{aligned}$$

Note that γ^* plays the double role of being a Lagrange multiplier to the forward-looking constraints $h_1(x, a, s) + \beta \mathrm{E}[\omega(\ell(x, a, s'), \varphi(\mu, \gamma), s')|s] \geq 0$ and an argument in the co-state transition $\varphi(\mu, \gamma)$. To prove the existence of such a saddle-point, we decompose these two roles. First, we show that for any $\widehat{\gamma} \in R_+^{l+1}$, in $\varphi(\mu, \widehat{\gamma})$, there is a saddle-point $(a^*(\widehat{\gamma}), \gamma^*(\widehat{\gamma}))$; then we use a fixed point argument to show that there is a γ^* satisfying $(a^*(\gamma^*), \gamma^*(\gamma^*))$. The former—that is, the existence of Lagrange multipliers—requires an interiority (or normality) condition, the latter to strengthen such interiority condition to guarantee that Lagrange multipliers are uniformly bounded. These conditions can take the following form:

IC. W, with $W = \mu\omega$, satisfies the *interiority condition* if, for any $(x, s) \in X \times S$, $\mu \in R_+^{l+1}$, and $j, j = 0, \dots, l$, there exists $\widetilde{a} \in A$, satisfying $p(x, \widetilde{a}, s) \geq 0$, and $h_1^j(x, \widetilde{a}, s) + \beta \mathrm{E}[\omega^j(\ell(x, \widetilde{a}, s'), \mu, s')|s] > 0$, and, for $i \neq j$, $h_1^i(x, \widetilde{a}, s) + \beta \mathrm{E}[\omega^i(\ell(x, \widetilde{a}, s'), \mu, s')|s] \geq 0$.[30]

SIC. W, with $W = \mu\omega$, satisfies the *strict interiority condition* if it satisfies **IC** and there exists an $\varepsilon > 0$ such that, for any $(x, , s) \in X \times S$, $\mu \in R_+^{l+1}$ and $j, \dots, l$, the inequality $h_1^j(x, \widetilde{a}, s) + \beta \mathrm{E}[\omega^j(\ell(x, \widetilde{a}, s'), \mu, s')|s] > 0$ in **IC** can be replaced by $h_1^j(x, \widetilde{a}, s) + \beta \mathrm{E}[\omega^j(\ell(x, \widetilde{a}, s'), \mu, s')|s] \geq \varepsilon$.

[29]Recall that Q satisfies the Feller property if whenever f is bounded and continuous in S, the function Tf given by $(Tf)(s) = \int f(s')Q(s, ds')$, for all $s \in S$, is also bounded and continuous on S. Assumption **A1** can be alternatively strengthened by assuming that S is countable and $\mathcal{S}$ is the σ-algebra containing all the subsets of S (see Stokey, Lucas, and Prescott (1989, 9.2)).

[30]Note that $\omega^j(\ell(x, \widetilde{a}, s'), \mu, s')$ can be replaced by $\omega^j(\ell(x, \widetilde{a}, s'), \varphi(\mu, \gamma), s')$, for any $\gamma \in R_+^{l+1}$.

The following lemma, which proof is immediate, provides a condition, easy to check, guaranteeing that these interiority conditions are satisfied.

LEMMA 2: *$W \in \mathcal{M}$, with $W = \mu\omega$, satisfies* **IC** (**SIC**) *if, for all $(x, s) \in X \times S$, $\mu \in R_+^{l+1}$, and $j = 0, \ldots, l$,*

$$\mathrm{E}\big[\omega^j\big(\ell(x, \widetilde{a}_0, s_0), \mu, s_1\big)|s_0\big] \geq \mathrm{E}\left[\sum_{t=0}^{N_j} \beta^t h_0^j(\widetilde{x}_t, \widetilde{a}_{t+1}, s_{t+1})|s_0\right],$$

for any i-interior program[31] *$\{\widetilde{a}_t\}_{t=0}^{\infty}$ of Assumption* **A7** (**A7s**), *$i = 0, \ldots, l$. Furthermore, if $W \in \mathcal{M}$ satisfies* **IC** (**SIC**), *then T^*W also satisfies* **IC** (**SIC**).

In other words, it is enough that $W \in \mathcal{W}$ takes the value of the interior programs of Assumption **A7** (**A7s**) as a lower bound to satisfy **IC** (**SIC**); for example, in the Section 2 example with limited enforcement constraints, **IC** (**SIC**) is satisfied if W guarantees that at any state (x, s), weights $\varphi(\mu, \gamma)$, and j, there is an interior (ϵ interior) allocation $\tilde{a}$ that allows agent j to satisfy its forward-looking constraint with strict inequality (ϵ inequality) while maintaining the forward-looking constraints of all the other agents. As Lemma 2 shows, given specific functional forms for $\mathbf{PP}_\mu$, it is not difficult to have $W \in \mathcal{M}$ satisfying these interiority conditions. Note that the last statement of Lemma 2 provides a guide to obtaining $W \in \mathcal{M}$ through value function iteration: start with a value function that satisfies the conditions of Lemma 2.

We can now state the main theorem of this section.

THEOREM 3: *Assume* **A1b** *and* **A2–A5** *and* **SIC**, *and* **A6** *when $\mathcal{M}$ refers to $\mathcal{M}_{bc}$.*

(i) *Let $W \in \mathcal{M}_{bc}$. For all $(x, \mu, s) \in X \times R_+^{l+1} \times S$, there exists $(\mathbf{a}^*, \boldsymbol{\gamma}^*)_{(x,\mu,s)}$ generated by $\Psi_W(x, \mu, s)$; that is, $(\mathbf{a}^*, \boldsymbol{\gamma}^*)_{(x,\mu,s)}$ satisfies (19)–(20). Furthermore, if* **A6s** *is assumed, then $(\mathbf{a}^*)_{(x,\mu,s)}$ is uniquely determined.*

(ii) *Let $W \in \mathcal{M}$ if, for all $(x, \mu, s) \in X \times R_+^{l+1} \times S$, $\Psi_W(x, \mu, s) \neq \emptyset$, then $T^*W \in \mathcal{M}$, that is, $T^*: \mathcal{M} \longrightarrow \mathcal{M}$.*

(iii) *Let $W \in \mathcal{M}$, if, for all $(x, \mu, s) \in X \times R_+^{l+1} \times S$, $\Psi_W(x, \mu, s) \neq \emptyset$, then $T^*: \mathcal{M} \longrightarrow \mathcal{M}$ is a contraction mapping of modulus β.*

PROOF: See Appendix D. *Q.E.D.*

Theorem 3(i) provides conditions for the existence of a *saddle-point*; (ii) establishes that the **SPFE** mapping is well defined by showing that T^* maps $\mathcal{M}$ onto itself, and finally, (iii) shows that T^* is a contraction mapping, therefore there is a unique value function $W \in \mathcal{M}$, $W = T^*W$, satisfying **SPFE**. This last result (iii) follows from the second (ii), Feller's property (**A1b**), and the fact that T^* satisfies Blackwell's sufficiency conditions for a contraction.

Theorem 3 shows how the standard dynamic programming results on the existence and uniqueness of a value function and the corresponding existence of optimal solutions generalize to our saddle-point dynamic programming approach, provided that an interiority condition is satisfied (e.g., **SIC**). As in standard dynamic programming, if $W \in \mathcal{M}_{bc}$ and the strict concavity assumption **A6s** is satisfied, then $(\mathbf{a}^*)_{(x,\mu,s)}$ is uniquely determined.

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[31] See Footnote 17.

Also as in standard dynamic programming, if these conditions are not satisfied and saddle-point solutions are not unique, an **SPFE** solution is a selection from the saddle-point correspondence. However, as we have seen in Section 3, when W is not differentiable in μ, a new kind of multiplicity arises.[32] Finally, Theorem 3 also shows that *the contraction property*—very practical for computing value functions—also extends to our *saddle-point Bellman equation operator*.

By Theorem 2, if $W = T^*W$ is differentiable in μ and $(\mathbf{a}^*, \boldsymbol{\gamma}^*)_{(x,\mu,s)}$ is generated by $\Psi_W(x, \mu, s)$, then $\mathbf{a}^*$ is a solution to $\mathbf{PP}_\mu$ at (x, s). Unfortunately, the subspace of differentiable functions is not a complete metric space and, therefore, T^* does not necessarily map μ- differentiable functions into μ-differentiable functions. However, we can provide more structure to T^* to guarantee that the generated solutions $(\mathbf{a}^*, \boldsymbol{\gamma}^*)_{(x,\mu,s)}$ satisfy the *Intertemporal Consistency Condition* **ICC**, and for this we define the T^{**} map. $T^{**} : \mathcal{M} \longrightarrow \mathcal{M}$ solves the same saddle-point problem as the T^* map, that is,

$$\begin{aligned}\big(T^{**}W\big)(x, \mu, s) = {} & \mathrm{SP}\min_{\gamma\geq 0}\max_{a}\big\{\mu h_0(x, a, s) + \gamma h_1(x, a, s) + \beta \mathrm{E}\big[W\big(x', \mu', s'\big)|s\big]\big\} \\ & \text{s.t. } x' = \ell\big(x, a, s'\big), \qquad p(x, a, s) \geq 0, \\ & \text{and } \mu' = \varphi(\mu, \gamma),\end{aligned}$$

but given $W \in \mathcal{M}$, takes a specific Euler representation $W = \mu\omega$ to define the Euler representation of $T^{**}W$ according to

$$\big(T^{**}\omega^j\big)(x, \mu, s) = h_0^j\big(x, a^*(x, \mu, s), s\big) + \beta \mathrm{E}\big[\omega^j\big(x^{*\prime}(x, \mu, s), \mu^{*\prime}(x, \mu, s), s'\big)|s\big],$$

if $j = 0, \dots, k$, and

$$\big(T^{**}\omega^j\big)(x, \mu, s) = h_0^j\big(x, a^*(x, \mu, s), s\big), \quad \text{if } j = k+1, \dots, l.$$

Given that T^{**} solves the same problem as T^*, the results of Theorem 3 hold for T^{**} and there is a $W \in \mathcal{M}$ such that $W = T^*W$ but, in addition, $\omega^j = T^{**}\omega^j$, for $j = 0, \dots, l$. Note that, even if W is unique, when it is not differentiable in μ it has multiple Euler representations and, correspondingly, the T^{**} map generates multiple solutions. Nevertheless, the **ICC** condition is satisfied. In sum, based on our Corollary to Theorem 2, we have the following result:

COROLLARY TO THEOREM 3: *Let $W \in \mathcal{M}$ satisfy $W = T^{**}W$, for a specific Euler representation $W = \mu\omega$, and $(\mathbf{a}^*, \boldsymbol{\gamma}^*)_{(x,\mu,s)}$ be generated by $\Psi_W(x, \mu, s)$; then $\mathbf{a}^*$ is a solution to $\mathbf{PP}_\mu$ at (x, s).*

Note that this corollary provides a guide to the user who is uncertain about whether $W \in \mathcal{M}$ is differentiable in μ : use the T^{**} map to get the $\mathbf{PP}_\mu$ solution, which simply takes the unique Euler representation when W is differentiable in μ, that is, in this case, T^{**} does the same as T^*.

[32]Note that it differs from the multiplicity in standard dynamic programming problems—that is, problems without forward-looking constraints—in an important aspect: in a standard dynamic problem, if at (x_t^*, s_t) there are multiple solutions, once one is "selected" leading to (x_{t+1}^*, s_{t+1}), the latter is a "sufficient statistic" in order to follow up on a solution path started at (x_0, s_0); in contrast, if at (x_t^*, μ_t^*, s_t) there are multiple saddle-point solutions (due to the fact that W is not differentiable in μ), once one is "selected" leading to $(x^{*\prime}, \mu^{*\prime}, s')$, the latter may not be a "sufficient statistic" in order to follow up on a solution path started at (x_0, μ_0, s_0).

5. RELATED WORK

Forward-looking constraints are pervasive in dynamic economic models. Early work introducing Lagrange multipliers as co-state variables in models of optimal policy are found in Epple, Hansen, and Roberds (1985), Sargent (1987), and Levine and Currie (1987) in linear-quadratic Ramsey problems, justified by the observation that past multipliers appear in the first-order conditions of the Ramsey problem. But this is only indicative of a recursive formulation. Our work provides a formal proof that introducing past multipliers as co-states delivers the optimal solution recursively in a general framework.

The promised-utility approach has been widely used in macroeconomics. Some applications are by Kocherlakota (1996) in a model with participation constraints similar to our Example 1, and Cronshaw and Luenberger (1994) in a dynamic game.[33] Moreover, Kydland and Prescott (1980), Chang (1998), and Phelan and Stacchetti (2001) studied Ramsey equilibria using promised *marginal* utility as a co-state variable, and they noted the analogy of their approach with promised utility.[34]

The promised-utility and our approach provide recursive characterizations of the solution to $\mathbf{PP}_\mu$. Obviously, both approaches provide the same solutions $\{a_t^*, x_t^*\}$, but they are conceptually and practically quite different. In our approach, the co-state variable is a vector μ_t satisfying a simple exogenous constraint: $\mu_t \in R_+^{l+1}$, while in the promised-utility approach, it is a vector—say, ω_t—which must satisfy an endogenous "promise-keeping" constraint.

A key difference between the two approaches lies in the fact that they define very different continuation problems. In the promised-utility approach, promised utility ω_t is a decision today for each possible future state, and this defines a state variable tomorrow, making the problem amenable to a standard Bellman equation treatment. This needs the computation of a correspondence for feasible utilities (denoted $\mathcal{C}_\kappa$) that is very hard to compute. However, as we have emphasized in Section 2, the continuation problem in our approach (namely, $\mathbf{PP}_{\mu_1^*}$) is guaranteed to have a solution for any $\mu_1^* \in R_+^{l+1}$. This entirely sidesteps any computation of the feasible set of co-state variables.

We now discuss these issues more concretely by formulating a recursive solution to Example 2 in the context of promised utilities. For ease of exposition, assume the exogenous shock g_t is i.i.d. and it can take ν possible values $\overline{g}^\kappa$, $\kappa = 1, \dots, \nu$, each with probability π^κ. Constraint (17) can be rewritten as

$$b_{t+1}\beta \sum_{\kappa=1}^{\nu} u'\big(c_{t+1}(\overline{g}^\kappa)\big)\pi^\kappa = u'(c_t)(b_t - c_t) - e_t v'(e_t). \tag{37}$$

Equation (37) is the "promise-keeping" constraint and $c_{t+1}(\overline{g}^\kappa)$ is the promised consumption in period $t+1$ if $g_{t+1} = \overline{g}^\kappa$ is realized. The key insight of the promised-utility approach is that by including all promised consumptions $(c_{t+1}(\overline{g}^1), \dots, c_{t+1}(\overline{g}^\nu))$ in the vector of today's decision variables a_t, equation (37) becomes a special case of a standard (backward-looking) constraint (2). This suggests we can apply the Bellman equation to conclude that the problem is recursive as long as realized consumption $\omega_t = c_t(g_t)$ is included as a co-state variable.

[33] Ljungqvist and Sargent (2018) provided an excellent introduction and references to most of this recent work.

[34] As we clarify in this paper—for example, in the discussion of Example 2 below—our approach is not the same as the approach of these papers.

But applying the Bellman equation to this reformulated problem without any further constraint would induce the planner to choose a $c_{t+1}(\overline{g}^{\kappa})$ that cannot be supported by any taxation scheme in equilibrium, so in this case the Bellman equation does not provide a feasible solution. To avoid this problem, one needs to compute for each κ the correspondence $\mathcal{C}_{\kappa}: R \to \mathcal{S}$, where $\mathcal{S}$ is a collection of subsets of R_{+} such that, if $c_{t+1}(\overline{g}^{\kappa}) \in \mathcal{C}_{\kappa}(b_{t+1})$ and if $g_{t+1} = \overline{g}^{\kappa}$, then a continuation tax and allocation process $\{\tau_{t+j}, c_{t+j}, b_{t+j+1},\}_{j=1}^{\infty}$ exists that is a competitive equilibrium with $c_{t+1} = c_{t+1}(\overline{g}^{\kappa})$ and corresponding inherited government debt b_{t+1}. Since the correspondence $\mathcal{C}_{\kappa}(\cdot)$ is an endogenous object, its computation is very complicated. For example, if there were J types of consumers in the above Ramsey model, J promised consumptions would have to be carried over as state variables, and in that case, we would need to compute multidimensional sets $\mathcal{C}_{\kappa}(b) \subset R_{+}^{J}$. Even though considerable progress has been made in the computation of the correspondence $\mathcal{C}_{\kappa}$, either by improving algorithms or by redefining the problem at hand,[35] this computation often leads to serious numerical difficulties. Most applications in the literature of the promised-utility approach assume there is no dependence on state variables (i.e., b does not influence C_{κ}) and the sets in S are subsets of R.

As we have seen in Section 2, the issue of computing a feasible set for promised consumption is entirely sidestepped in our approach. This is because any γ_{t-1}^{*1} gives a well-defined continuous objective function of $\mathbf{PP}_{\mu_t^*}$, so that this continuation problem always has a solution.[36]

An additional advantage of the Lagrangian approach is that it leads to a reduction in the number of decision and state variables. We have only two decision variables (c_t, b_{t+1}) in Example 2 under our approach at t, while in the promised-utility approach, there are $\nu + 1$ decision variables $(c_{t+1}(\overline{g}^1), \dots, c_{t+1}(\overline{g}^{\nu}), b_{t+1})$ at t.

As is well known, the highest computational savings come from a reduction in the dimension of the state vector. In some cases, the recursive Lagrangian has many fewer state variables. Consider generalizing Example 2 to the case where the government issues one long bond that matures in M periods and long bonds are not repurchased by the government, as in Faraglia, Marcet, Oikonomou, and Scott (2016, 2019). In this case, the bond price depends on the expectation of marginal utility M periods ahead, so that the analog of (37) gives

$$b_{t+1}^{M}\beta^{M} \sum_{\widetilde{g}^{M} \in G^{M}} u'\big(c_{t+M}\big(g_t, \widetilde{g}^{M}\big)\big)\widetilde{\pi}\big(\widetilde{g}^{M}\big) = u'(c_t)\big(b_{t-M+1}^{M} - c_t\big) - e_t v'(e_t), \tag{38}$$

where we denote G^i the set of all possible realizations of $(g_{t+1}, \dots, g_{t+i})$, and $\widetilde{\pi}^{\kappa}(\widetilde{g}^{M})$ the probability of each sequence. Clearly, the co-state using promised-utility includes $\omega_t = (c_t, [c_{t+i}(g_t, \widetilde{g}^i)]_{\widetilde{g}^i \in G^i}^{i=1,\dots,M-1})$. For a 10-year bond, even if g only takes two possible values so $\nu = 2$, a quarterly version of the model has more than one trillion state variables, since G^i has 2^i elements.[37] By comparison, the Lagrangian approach can be implemented with "only" $2M + 1 = 81$ state variables $(\gamma_{t-1}, \dots, \gamma_{t-M}, b_t^M, \dots, b_{t-M+1}^M, g_t)$.[38]

[35]See, for example, Ábrahám and Pavoni (2005) or Judd, Yeltekin, and Conklin (2003).

[36]See the discussion following equation (18).

[37]There are ways of reducing this problem; Lustig, Sleet, and Yeltekin (2008) provided a recursive formulation with long bonds by adding the yield curve as a state variable. The issue then becomes one of formulating a very high-dimensional feasible set for the yield curve which ensures that the continuation problem is well-defined.

[38]See Faraglia, Marcet, Oikonomou, and Scott (2019, Section 3 for details, and Sections 5, 6, 7 for the state variables in several variations of the model).

There are some additional differences between the two approaches. Initial conditions for the co-state variables in our approach are known from the outset to be $\mu_0^0 = 1$, $\mu_0^1 = 0$, but in the promised-utility approach, the initial condition is c_0, which needs to be solved for separately, since it is an endogenous variable. This is because, as pointed out before, the promised-utility approach determines the variable one period ahead, so it needs an ending boundary condition, while our approach starts out from a given initial condition. It is well known that to find c_0, the Pareto frontier has to be downward sloping; otherwise, the computations can become very cumbersome.

The co-state variables in our approach often have an economic interpretation. We have already described in Section 2 how the evolution of μ_t^* can unveil the reason for time-inconsistency problems. Also, μ_t^* can be interpreted as time-varying Pareto weights in Example 1 and a time-varying deadweight loss of taxation in Example 2.

Early versions of this paper conceded as an advantage of promised-utility that it could be applied to models under moral hazard and incentive constraints. However, Messner, Pavoni, and Sleet (2012) and Mele (2014) have extended our approach to address moral hazard problems, and Ábrahám, Cárceles-Poveda, Liu, and Marimon (2019) study a risk-sharing partnership with intertemporal participation and moral hazard constraints. Thus, the initial advantages of the promised-utility approach seem to have mostly vanished.

6. CONCLUDING REMARKS

We have shown that a large class of problems with *forward-looking* constraints can be conveniently formalized as a saddle-point problem. This saddle-point problem obeys a *saddle-point functional equation* (**SPFE**) which is analogous to the Bellman equation. The approach works for a very large class of models with incentive constraints: intertemporal enforcement constraints, intertemporal Euler equations in optimal policy and regulation design, etc. We provide a unified framework for the analysis of all these models. The key feature of our approach is that instead of having to write optimal contracts as history-dependent contracts, one can write them as a time-invariant function of the standard state variables together with additional co-state variables. These co-state variables are recursively obtained from the Lagrange multipliers associated with the forward-looking constraints, starting from pre-specified initial conditions. This simple representation also provides economic insight into the analysis of various contractual problems. For example, with intertemporal participation constraints, it shows how the (Benthamite) social planner changes the weights assigned to different agents in order to keep them within the social contract; in Ramsey optimal problems, it shows the cost of commitment when the policies of a benevolent government are not time-consistent.

This paper provides the first complete account of the basic theory of *recursive contracts*. We have already presented most of the elements of the theory in our previous work (in particular, Marcet and Marimon (1998 and 2011)), which has allowed others to build on it. Many applications are already found in the literature, showing the convenience of our approach, especially when: natural state variables, such as capital or debt, are present; the solution (of a planner's or Ramsey problem) is not time-consistent; our co-state variable μ plays a key rule in determining constrained efficiency wedges, or contracts need to be decentralized and, therefore, priced. Similarly, extensions are already available, encompassing a wider set of problems than those considered here (moral hazard, endogenous participation constraints, etc.). Our sufficiency result when the value function is differentiable (in μ)—as in the case that the constrained efficient allocation is unique—already covers a wide range of frequently studied economies. We broaden this range to a larger set of economies (e.g., weakly concave with multiple solutions) by providing the *intertemporal consistency condition* (**ICC**) that must be satisfied when there are forward-looking constraints—a condition that is always satisfied when the value function is differentiable (in μ). In the more general case, we show how ICC can be guaranteed when the saddle-point functional equation has a solution.[39] Finally, we also provide conditions for the existence of solutions to our *saddle-point functional equation* (**SPFE**) and extend the main results of dynamic programming to our saddle-point formulation.

APPENDIX A: REARRANGING THE LAGRANGIAN

Here we show that $\mathcal{L}_\mu$ as defined in (4) is equivalent to (5). Shifting E_t in the second line of (4), we can rewrite $\mathcal{L}_\mu$ as

$$\begin{aligned} &\mathcal{L}_\mu(\boldsymbol{a}, \boldsymbol{\gamma}; x, s) \\ &\quad = \mathrm{E}_0\Bigg[\sum_{j=0}^{l}\sum_{t=0}^{N_j}\beta^t \mu^j h_0^j(x_t, a_t, s_t) \\ &\qquad + \mathrm{E}_t \sum_{t=0}^{\infty}\beta^t \sum_{j=0}^{l}\gamma_t^j \sum_{n=1}^{N_j+1}\beta^n\big(h_0^j(x_{t+n}, a_{t+n}, s_{t+n}) + h_1^j(x_t, a_t, s_t)\big)|s_0\Bigg]. \end{aligned} \tag{39}$$

This holds because there is one forward-looking constraint (3) for each possible sequence of shocks s^t, hence γ_t^j is a function of s^t and can be included inside E_t. Using the law of iterated expectations, this implies that E_t can be deleted from the second line of (39). We take this for granted in the remainder of Appendix A.

Now, fix a period $\bar{t} \geq 0$ and a $j \leq k$, so that $N_j = \infty$. We see that in the total sum defining $\mathcal{L}_\mu$, the term $h_0^j(x_{\bar{t}}, a_{\bar{t}}, s_{\bar{t}})$ appears in the first line of (39)—the objective function of $\mathbf{PP}_\mu$—premultiplied by $\beta^{\bar{t}}\mu^j$. This term also appears in the second line of (39) in the forward-looking constraints (3) at all $t \leq \bar{t}$; in the second line, it is multiplied by the discounting β^n for $n = \bar{t} - t$ and then again by β^t. Therefore, in the total sum in (39), $Q(s^t|s_0)h_0^j(x_{\bar{t}}, a_{\bar{t}}, s_{\bar{t}})$ is multiplied by the following term:

$$\beta^{\bar{t}}\mu^j + \gamma_0^j\beta^{\bar{t}} + \beta^1\gamma_1^j\beta^{\bar{t}-1} + \cdots + \beta^{\bar{t}-1}\gamma_{\bar{t}-1}^j\beta^1 = \beta^{\bar{t}}\Bigg[\sum_{i=0}^{\bar{t}-1}\gamma_i^j + \mu^j\Bigg] = \beta^{\bar{t}}\mu_{\bar{t}}^j.$$

The equalities follow from simple algebra, (6), and $j \leq k$. This gives that (4) and (5) are equivalent for $j \leq k$.

Similarly, fix $\bar{t} \geq 0$ for $j > k$ so that $N_j = 0$. Then $h_0^j(x_{\bar{t}}, a_{\bar{t}}, s_{\bar{t}})$ for $\bar{t} > 0$ appears in the first line of $\mathcal{L}_\mu$ premultiplied by $\beta^0\mu^j$ and it does not appear in the second line. For $\bar{t} > 0$, the term appears once in the forward-looking constraint of $\bar{t} - 1$, therefore multiplied by $\beta^{\bar{t}-1}\gamma_{\bar{t}-1}^j\beta^1$. Given (6) for $j > k$, we have $\mu_{\bar{t}}^j = \gamma_{t-1}$ for $\bar{t} > 0$ and $\mu_0^j = \mu^j$, so that the term $h_0^j(x_{\bar{t}}, a_{\bar{t}}, s_{\bar{t}})$ is multiplied in the total sum above by $\beta^{\bar{t}}\mu_{\bar{t}}^j$.

Hence (4) and (5) are equivalent.

[39] Cole and Kubler (2012) provided a generalization to the non-uniqueness case for a restricted class of models. Marimon and Werner (2019) follow our approach more closely and, applying their extension of the envelope theorem, provide a recursive formulation for the non-differentiable case.

APPENDIX B: PROOFS OF THEOREMS 1 AND 2 AND PROPOSITION 1

The Infinite-Dimensional Formulation

For some of the proofs, it is convenient to describe the *infinite-dimensional* formulation of $\mathbf{PP}_\mu$. The underlying uncertainty takes the form of an exogenous stochastic process $\{s_t\}_{t=0}^\infty$, $s_t \in S$, defined on the probability space $(S_\infty, \mathcal{S}, P)$. As usual, s^t denotes a history $(s_0, \dots, s_t) \in S_t$, $\mathcal{S}_t$ the σ-algebra of events of s^t and $\{s_t\}_{t=0}^\infty \in S_\infty$, with $\mathcal{S}$ the corresponding σ-algebra. An action in period t, history s^t, is denoted by $a_t(s^t)$, where $a_t(s^t) \in A \subset R^m$. When there is no confusion, it is simply denoted by a_t. Plans, $\boldsymbol{a} = \{a_t\}_{t=0}^\infty$, are elements of $\mathcal{A} = \{\boldsymbol{a} : \forall t \geq 0, a_t : S_t \to A \text{ and } a_t \in \mathcal{L}_\infty^m(S_t, \mathcal{S}_t, P)\}$, where $\mathcal{L}_\infty^m(S_t, \mathcal{S}_t, P)$ denotes the space of m-valued, essentially bounded, $\mathcal{S}_t$-measurable functions. The corresponding endogenous state variables are elements of $\mathcal{X} = \{\boldsymbol{x} : \forall t \geq 0, x_t \in \mathcal{L}_\infty^n(S_t, \mathcal{S}_t, P)\}$.

We now define preferences, sets of feasible actions, and problems, given initial conditions (x, s). A plan $\boldsymbol{a} \in \mathcal{A}$ and a corresponding $\boldsymbol{x} \in \mathcal{X}$ are evaluated in $\mathbf{PP}_\mu$ by

$$f_{(x,\mu.s)}(\boldsymbol{a}) = \mathrm{E}_0 \sum_{j=0}^{l} \sum_{t=0}^{N_j} \beta^t \mu^j h_0^j(x_t, a_t, s_t).$$

We can describe the forward-looking constraints, coordinatewise, $g_{(x,s)}(\cdot)_t : \mathcal{A} \to \mathcal{L}_\infty^{l+1}(S_t, \mathcal{S}_t, P)$ by

$$g_{(x,s)}(\boldsymbol{a})_t^j = \mathrm{E}_t\left[\sum_{n=1}^{N_j+1} \beta^n h_0^j(x_{t+n}, a_{t+n}, s_{t+n})\right] + h_1^j(x_t, a_t, s_t).$$

The corresponding feasible set of plans is then

$$\mathcal{B}(x, s) = \big\{\boldsymbol{a} \in \mathcal{A} : p(x_t, a_t, s_t) \geq 0, g_{(x,s)}(\boldsymbol{a})_t \geq 0, \boldsymbol{x} \in \mathcal{X},$$
$$x_{t+1} = \ell(x_t, a_t, s_{t+1}) \text{ for all } t \geq 0, \text{ given } (x_0, s_0) = (x, s)\big\}.$$

Therefore, the $\mathbf{PP}_\mu$ can be written in compact form as

$$\mathbf{PP}_\mu \quad \sup_{\boldsymbol{a} \in \mathcal{B}(x,s)} f_{(x,\mu.s)}(\boldsymbol{a}). \tag{40}$$

We denote solutions to this problem as $\boldsymbol{a}^*$ and the corresponding sequence of state variables as $\boldsymbol{x}^*$. When the solution exists, the value function of $\mathbf{PP}_\mu$ can be written as $V_\mu(x, s) = f_{(x,\mu.s)}(\boldsymbol{a}^*)$. It will be useful to consider a feasible set that disregards the forward-looking constraints in the initial period, resulting in

$$\mathcal{B}'(x, s) = \big\{\boldsymbol{a} \in \mathcal{A} : p(x_t, a_t, s_t) \geq 0, g_{(x,s)}(\boldsymbol{a})_{t+1} \geq 0; \boldsymbol{x} \in \mathcal{X},$$
$$x_{t+1} = \ell(x_t, a_t, s_{t+1}) \text{ for all } t \geq 0, \text{ given } (x_0, s_0) = (x, s)\big\}.$$

Then, the $\mathbf{SPP}_\mu$ problem defined above can be written using this formulation as

$$\mathbf{SPP}_\mu \quad \mathrm{SP} \inf_{\gamma \in R_+^l} \sup_{\boldsymbol{a} \in \mathcal{B}'(x,s)} \big\{f_{(x,\mu,.s)}(\boldsymbol{a}) + \gamma g_{(x,s)}(\boldsymbol{a})_0\big\}.$$

PROOF OF THEOREM 1 PART I ($\mathbf{SPP}_\mu \Rightarrow \mathbf{PP}_\mu$): It follows from Theorem 2, Section 8.4 in Luenberger (1969, p. 221) that $\boldsymbol{a}^*$ solves $\mathbf{PP}_\mu$ and the value at the saddle-point is the same as the value at the maximum, hence $SV(x, \mu, s) = V_\mu(x, s)$. *Q.E.D.*

PROOF OF THEOREM 1 PART II ($\mathbf{SPP}_\mu \Rightarrow \mathbf{SPFE}$): We need to show that $W(x,\mu,s) = V_\mu(x,s) = SV(x,\mu,s)$ satisfies the **SPFE** and that the period-zero solution of $\mathbf{SPP}_\mu$ at (x,s), namely, (a_0^*, γ_0^*), is a saddle-point of **SPFE** at (x,μ,s).

First, we show that, given γ_0^*, a_0^* satisfies the maximand part (20) for $W = SV$. Take any $\widetilde{a} \in A$ such that $p(x,\widetilde{a},s) \geq 0$. Consider the sequence obtained by starting at $\widetilde{a}$ and then continuing to the optimal solution of $\mathbf{PP}_{\mu_1^*}$ from $t = 1$ onwards given initial condition $\widetilde{x}_1 = \ell(x,\widetilde{a},s_1)$. To properly express this, we introduce some notation. Let the shift operator $\sigma : S^{t+1} \to S^t$ be given by $\sigma(s^t) \equiv \sigma(s_0, s_1, \ldots, s_t) = (s_1, s_2, \ldots, s_t)$, and—denoting $(\boldsymbol{a}^*(x,\mu,s), \gamma^*(x,\mu,s))$ a solution to $\mathbf{SPP}_\mu$ at (x,s)—let the solution plan following a deviation $\widetilde{a}$ have the following representation:

$$\widetilde{a}_0(x,\mu,s) = \widetilde{a} \quad \text{and}$$
$$\widetilde{a}_t(x,\mu,s)(s^t) = a_{t-1}^*\big(\widetilde{x}_1, \mu_1^*(x,\mu,s), s_1\big)\big(\sigma(s^t)\big) \quad \text{for all } t > 0.$$

Part I of this theorem and the definition of $\mathbf{PP}_{\mu_1^*}$ imply that

$$\mathrm{E}\big[SV\big(\widetilde{x}_1, \mu_1^*, s_1\big)|s\big] = \mathrm{E}\big[V_{\mu_1^*}(\widetilde{x}_1, s_1)|s\big] = \mathrm{E}_0 \sum_{j=0}^{l} \mu_1^{*j} \sum_{t=0}^{N_j} \beta^t h_0^j(\widetilde{x}_{t+1}, \widetilde{a}_{t+1}, s_{t+1}). \tag{41}$$

Since the sequence $\widetilde{\boldsymbol{a}}$ is feasible for $\mathbf{SPP}_\mu$ (i.e., $\widetilde{\boldsymbol{a}}$ may fail the forward-looking constraint at $t = 0$, but recall that this constraint does not constrain the feasible set in $\mathbf{SPP}_\mu$) and since $\boldsymbol{a}^*(x,\mu,s)$ solves the *sup* part of $\mathbf{SPP}_\mu$, given (41) we have the first inequality in

$$\begin{aligned}
&\mu h_0(x,\widetilde{a},s) + \gamma^* h_1(x,\widetilde{a},s) + \beta \mathrm{E}\big[SV\big(\widetilde{x}_1, \mu_1^*, s_1\big)|s\big] \\
&\quad \leq \mu h_0\big(x, a_0^*, s\big) + \gamma^* h_1\big(x, a_0^*, s\big) + \beta \mathrm{E}_0 \sum_{j=0}^{l} \mu_1^{*j} \sum_{t=0}^{N_j} \beta^t h_0^j\big(x_{t+1}^*, a_{t+1}^*, s_{t+1}\big) \\
&\quad = \mu h_0\big(x, a_0^*, s\big) + \gamma^* h_1\big(x, a_0^*, s\big) + \beta \mathrm{E}\big[SV\big(x_1^*, \mu_1^*, s_1\big)|s\big].
\end{aligned}$$

The equality follows because (41) also works when $\widetilde{\boldsymbol{a}}$ is replaced by $\boldsymbol{a}^*(x,\mu,s)$.

This proves that a_0^* satisfies (20) when $W = SV$.

To show that γ_0^* satisfies (19), note that, given any $\widetilde{\gamma} \in R_+^{l+1}$,

$$\begin{aligned}
\mathrm{E}\big[SV\big(x_1^*, \varphi(\mu,\widetilde{\gamma}), s_1\big)|s\big] &= \mathrm{E}\big[V_{\varphi(\mu,\widetilde{\gamma})}\big(x_1^*, s_1\big)|s\big] \\
&\geq \mathrm{E}\left[\sum_{j=0}^{l} \varphi(\mu,\widetilde{\gamma})^j \sum_{t=0}^{N_j} \beta^t h_0^j\big(x_{t+1}^*, a_{t+1}^*, s_{t+1}\big) \mid s\right],
\end{aligned}$$

where the inequality follows from the fact that the continuation of $\boldsymbol{a}^*$ is feasible but not necessarily optimal for $\mathbf{PP}_{\varphi(\mu,\widetilde{\gamma})}$ at (x_1^*, s_1). Using this and the fact that γ^* solves the min part of $\mathbf{SPP}_\mu$, we have

$$\begin{aligned}
&\mu h_0\big(x, a_0^*, s\big) + \widetilde{\gamma} h_1\big(x, a_0^*, s\big) + \beta \mathrm{E}\big[SV\big(x_1^*, \varphi(\mu,\widetilde{\gamma}), s_1\big)|s\big] \\
&\quad \geq \mu h_0\big(x, a_0^*, s\big) + \widetilde{\gamma} h_1\big(x, a_0^*, s\big) + \beta \mathrm{E}\left[\sum_{j=0}^{l} \varphi(\mu,\widetilde{\gamma})^j \sum_{t=0}^{N_j} \beta^t h_0^j\big(x_{t+1}^*, a_{t+1}^*, s_{t+1}\big) \mid s\right] \\
&\quad \geq \mu h_0\big(x, a_0^*, s\big) + \gamma^* h_1\big(x, a_0^*, s\big) + \beta \mathrm{E}\big[SV\big(x_1^*, \varphi\big(\mu, \gamma^*\big), s_1\big)|s\big].
\end{aligned}$$

This proves that $(a_0^*, \gamma_0^*) \in \Psi_{SV}(x, \mu, s)$. Finally, using the definition of SV in (21), we have

$$SV(x, \mu, s) = \mu h_0(x, a_0^*, s) + \gamma^* h_1(x, a_0^*, s) + \beta \mathrm{E}[SV(x_1^*, \varphi(\mu, \gamma^*), s')|s]. \tag{42}$$

Therefore, SV satisfies **SPFE**. *Q.E.D.*

PROOF OF COROLLARY TO THEOREM 1: We have to show that, with the additional assumptions, $(\mathbf{PP}_\mu \Rightarrow \mathbf{SPP})_\mu$, that is, there exists a $\gamma^* \in R_+^{l+1}$ such that $(\boldsymbol{a}^*, \gamma^*)$ is a solution to $\mathbf{SPP}_\mu$ with initial conditions (x, s). With the above formulation (40), this is an immediate application of Theorem 1 (8.3) and Corollary 1 in Luenberger (1969, p. 217). To see this, note that $\mathcal{B}'(x, s)$ is a convex subset of $\mathcal{A}$, $g_{(x,s)}(\cdot)_0 : \mathcal{A} \to \mathcal{L}_\infty^{l+1}(S_0, \mathcal{S}_0, P)$, and by Assumption **A7**,[40] there is an $\widetilde{\boldsymbol{a}} \in \mathcal{B}'(x, s)$ such that $g_{(x,s)}(\widetilde{\boldsymbol{a}})_0 > 0$. *Q.E.D.*

PROOF OF PROPOSITION 1: Let $\widehat{S}_1 \subset S$ be the set such that, if $s_1 \in \widehat{S}_1$, then

$$V_{\mu_1^*}(x_1^*, s_1) > \mathrm{E}\left[\sum_{j=0}^{l} \sum_{t=0}^{N_j} \beta^t \mu_1^{*j} h_0^j(x_{t+1}^*, a_{t+1}^*, s_{t+1}) \mid s_1\right].$$

We will show that $\widehat{S}_1$ has probability zero.

The constraints in $\mathbf{PP}_{\mu_1^*}$ are a subset of the constraints in $\mathbf{PP}_\mu$. Therefore, the continuation for $\boldsymbol{a}^*$, namely $\{a_t^*\}_{t=1}^\infty$, is feasible for $\mathbf{PP}_{\mu_1^*}$ with initial conditions (x_1^*, s_1). If $\widehat{s}_1 \in \widehat{S}_1$, there must exist a plan $\{\widehat{a}_t\}_{t=0}^\infty$ achieving a higher value than the value achieved by $\{a_t^*\}_{t=1}^\infty$ for $\mathbf{PP}_{\mu_1^*}$ with initial conditions $(x_1^*, \widehat{s}_1)$ so that

$$\begin{aligned} &\mathrm{E}\left[\sum_{j=0}^{l} \mu_1^{j*} \sum_{t=0}^{N_j} \beta^t h_0^j(x_{t+1}^*, a_{t+1}^*, s_{t+1}) \mid s_1 = \widehat{s}_1\right] \\ &\quad < \mathrm{E}\left[\sum_{j=0}^{l} \mu_1^{j*} \sum_{t=0}^{N_j} \beta^t h_0^j(\widehat{x}_t, \widehat{a}_t, s_t) \mid s = \widehat{s}_1\right]. \end{aligned} \tag{43}$$

Denote by $\widetilde{\boldsymbol{a}}$ an allocation such that $\widetilde{a}_0 = a_0^*$; it maintains the saddle-point for $t > 0$ so $\{\widetilde{a}_t\}_{t=1}^\infty = \{a_t^*\}_{t=1}^\infty$ if $s_1 \in S \backslash \widehat{S}_1$, while the solution switches so $\{\widetilde{a}_t\}_{t=1}^\infty = \{\widehat{a}_t\}_{t=0}^\infty$ if $s_1 \in \widehat{S}_1$. If $\mathrm{Prob}(\widehat{S}_1) > 0$, we have

$$\begin{aligned} &\mu h_0(x_0, a_0^*, s_0) + \gamma_0^* h_1(x_0, a_0^*, s_0) + \beta \mathrm{E}\left[\sum_{j=0}^{l} \mu_1^{j*} \sum_{t=0}^{N_j} \beta^t h_0^j(x_{t+1}^*, a_{t+1}^*, s_{t+1}) \mid s_0\right] \\ &\quad < \mu h_0(x_0, a_0^*, s_0) + \gamma_0^* h_1(x_0, a_0^*, s_0) \\ &\qquad + \beta \mathrm{E}\left[\mathrm{E}\left[\sum_{j=0}^{l} \mu_1^{j*} \sum_{t=0}^{N_j} \beta^t h_0^j(\widehat{x}_t, \widehat{a}_t, s_t) \mid s_1 \in \widehat{S}_1\right] \Bigg| s_0\right] \end{aligned}$$

[40]As already noted, Assumption **A7** is weaker than the standard Slater's condition but, when the concavity assumption **A6** is satisfied, it is equivalent.

$$+\beta \mathrm{E}\left[\mathrm{E}\left[\sum_{j=0}^{l}\mu_1^{j*}\sum_{t=0}^{N_j}\beta^t h_0^j\big(x_{t+1}^*, a_{t+1}^*, s_{t+1}\big) \mid s_1 \in S\backslash\widehat{S}_1\right] \mid s_0\right]$$

$$= \mu h_0(x_0, \widetilde{a}_0, s_0) + \gamma_0^* h_1(x_0, \widetilde{a}_0, s_0) + \beta \mathrm{E}\left[\sum_{j=0}^{l}\mu_1^{j*}\sum_{t=0}^{N_j}\beta^t h_0^j(\widetilde{x}_{t+1}, \widetilde{a}_{t+1}, s_{t+1}) \mid s_0\right],$$

where the inequality follows from (43).

Finally, note that the plan $\widetilde{\boldsymbol{a}}$ is feasible for $\mathbf{SPP}_\mu$. This is because since $\{\widehat{a}_t\}_{t=0}^\infty$ solves $\mathbf{PP}_{\mu_1^*}$, it satisfies the constraints in (23) (note that $\widetilde{\boldsymbol{a}}$ will generically violate the forward-looking constraint at $t=0$, but this constraint is absent in (23)). Therefore, the above inequality contradicts that $\boldsymbol{a}^*$ solves the max part of $\mathbf{SPP}_\mu$ with initial conditions (x, s) and it contradicts the assumption that $(\boldsymbol{a}^*, \gamma_0^*)$ is a saddle-point of $\mathbf{SPP}_\mu$. It follows that $\mathrm{Prob}(\widehat{S}_1) = 0$ or, equivalently, $V_{\mu_1^*}(x_1^*, s_1) \leq \mathrm{E}[\sum_{j=0}^{l}\sum_{t=0}^{N_j}\beta^t\mu_1^{*j}h_0^j(x_{t+1}^*, a_{t+1}^*, s_{t+1}) \mid s_1]$ a.s.

Using, again, the fact that the continuation of a feasible sequence for $\mathbf{PP}_\mu$ satisfies the constraints of $\mathbf{PP}_{\mu_1^*}$, we have $V_{\mu_1^*}(x_1^*, s_1) \geq \mathrm{E}[\sum_{j=0}^{l}\sum_{t=0}^{N_j}\beta^t\mu_1^{*j}h_0^j(x_{t+1}^*, a_{t+1}^*, s_{t+1}) \mid s_1]$.

Therefore, $V_{\mu_1^*}(x_1^*, s_1) = \mathrm{E}[\sum_{j=0}^{l}\sum_{t=0}^{N_j}\beta^t\mu_1^{*j}h_0^j(x_{t+1}^*, a_{t+1}^*, s_{t+1}) \mid s_1]$ a.s. and $\{a_t^*\}_{t=1}^\infty$ solves $\mathbf{PP}_{\mu_1^*}$ with initial conditions (x_1^*, s_1) a.s. *Q.E.D.*

PROOF OF THEOREM 2 PART II: We need to show that if $(\mathbf{a}^*, \boldsymbol{\gamma}^*)_{(x,\mu,s)}$ is generated by the saddle-point policy correspondence Ψ_W (i.e., $(a_t^*, \gamma_t^*) \in \Psi_W(x_t^*, \mu_t^*, s_t)$ for every (t, s_t)), then $\mathbf{a}^*$ is a solution to $\mathbf{PP}_\mu$ at (x, s), already knowing that it satisfies the constraints of $\mathbf{PP}_\mu$. In particular, if there is a program $\{\widetilde{a}_t\}_{t=0}^\infty$, and $\{\widetilde{x}_t\}_{t=0}^\infty$, given by $\widetilde{x}_0 = x, \widetilde{x}_{t+1} = \ell(\widetilde{x}_t, \widetilde{a}_t, s_{t+1})$, satisfying the constraints of $\mathbf{PP}_\mu$ with initial condition (x, s), then this program cannot result in a higher value than $W(x, \mu, s)$. To this end, note that the maximality condition (20) can be expressed as

$$\begin{aligned}&\mu h_0\big(x, a^*, s\big) + \gamma^* h_1\big(x, a^*, s\big) + \beta \mathrm{E}\big[\varphi\big(\mu, \gamma^*\big)\omega\big(x^{*\prime}, \varphi\big(\mu, \gamma^*\big), s'\big)|s\big]\\ &\quad\geq \mu h_0(x, a, s) + \gamma^* h_1(x, a, s) + \beta \mathrm{E}\big[\varphi\big(\mu, \gamma^*\big)\omega\big(x', \varphi\big(\mu, \gamma^*\big), s'\big)|s\big] \qquad (44)\end{aligned}$$

and

$$W\big(x_t^*, \mu_t^*, s_t\big) = \mu_t^* h_0\big(x_t^*, a_t^*, s_t\big) + \gamma_t^* h_1\big(x_t^*, a_t^*, s_t\big) + \beta \mathrm{E}\big[W\big(x_{t+1}^*, \varphi\big(\mu_t^*, \gamma_t^*\big), s_{t+1}\big)|s_t\big]. \quad (45)$$

Furthermore, to simplify the notation, let $\mu_1^* = \varphi(\mu, \gamma_0^*)$, $\widetilde{\mu}_2^* = \varphi(\mu_1^*, \gamma_1^*(\widetilde{x}_1))$[41] and, for $t > 1$, $\widetilde{\mu}_{t+1}^* = \varphi(\widetilde{\mu}_t^*, \gamma_t^*(\widetilde{x}_t))$; that is, $\widetilde{\mu}_t^*$ is the co-state for the deviation plan. In what follows, we proceed by iteration of the **SPFE** (max) inequality, (44), and we expand the value function according to (45). In particular, inequalities (46), (48), and (51) apply the inequality (44), and the equalities (47) and (50) apply the equality (45), while equality (49) simply rearranges terms and (52) uses the transversality condition, $\lim_{T\longrightarrow\infty}\beta^T W = 0$. We conclude the proof of the max part of **SPP** by showing that the left-hand side of (46) is greater than or equal to (53):

$$\begin{aligned}&\mu h_0\big(x, a_0^*, s\big) + \gamma_0^* h_1\big(x, a_0^*, s\big) + \beta\varphi\big(\mu, \gamma_0^*\big)\mathrm{E}\big[\omega\big(\ell\big(x, a_0^*, s_1\big), \varphi\big(\mu, \gamma_0^*\big), s_1\big)|s\big]\\ &\quad\geq \mu h_0(x, \widetilde{a}_0, s) + \gamma_0^* h_1(x, \widetilde{a}_0, s) + \beta\varphi\big(\mu, \gamma_0^*\big)\mathrm{E}\big[\omega\big(\ell(x, \widetilde{a}_0, s_1), \varphi\big(\mu, \gamma_0^*\big), s_1\big)|s\big] \qquad (46)\end{aligned}$$

[41]We also simplify notation by writing simply $\gamma_1^*(\widetilde{x}_1)$ instead of $\gamma_1^*(\widetilde{x}_1, \mu_1^*, s_1)$.

$$
\begin{aligned}
&= \mu h_0(x, \widetilde{a}_0, s) + \gamma_0^* h_1(x, \widetilde{a}_0, s) \\
&\quad + \beta \mathrm{E} \mu_1^* \big[h_0\big(\widetilde{x}_1, a_1^*(\widetilde{x}_1), s_1\big) + \beta \mathrm{E}\big[I^k \omega\big(\ell\big(\widetilde{x}_1, a_1^*(\widetilde{x}_1), s_2\big), \varphi\big(\mu_1^*, \gamma_1^*(\widetilde{x}_1)\big), s_2\big) | s_1 \big] | s \big] \\
&\quad + \beta \mathrm{E} \gamma_1^*(\widetilde{x}_1) \big[h_1\big(\widetilde{x}_1, a_1^*(\widetilde{x}_1), s_1\big) \\
&\quad + \beta \mathrm{E}\big[\omega\big(\ell\big(\widetilde{x}_1, a_1^*(\widetilde{x}_1), s_2\big), \varphi\big(\mu_1^*, \gamma_1^*(\widetilde{x}_1)\big), s_2\big) | s_1 \big] | s \big] && (47) \\
&\geq \mu h_0(x, \widetilde{a}_0, s) + \gamma_0^* h_1(x, \widetilde{a}_0, s) \\
&\quad + \beta \mathrm{E} \mu_1^* \big[h_0(\widetilde{x}_1, \widetilde{a}_1, s_1) + \beta \mathrm{E}\big[I^k \omega\big(\ell(\widetilde{x}_1, \widetilde{a}_1, s_2), \varphi\big(\mu_1^*, \gamma_1^*(\widetilde{x}_1)\big), s_2\big) | s_1 \big] | s \big] \\
&\quad + \beta \mathrm{E} \gamma_1^*(\widetilde{x}_1) \big[h_1(\widetilde{x}_1, \widetilde{a}_1, s_1) + \beta \mathrm{E}\big[\omega\big(\ell(\widetilde{x}_1, \widetilde{a}_1, s_2), \varphi\big(\mu_1^*, \gamma_1^*(\widetilde{x}_1)\big), s_2\big) | s_1 \big] | s \big] && (48) \\
&= \mu \big[h_0(x, \widetilde{a}_0, s) + \beta \mathrm{E}\big[I^k h_0(\widetilde{x}_1, \widetilde{a}_1, s_1) | s \big] \big] \\
&\quad + \gamma_0^* \big[h_1(x, \widetilde{a}_0, s) + \beta \mathrm{E}\big[h_0(\widetilde{x}_1, \widetilde{a}_1, s_1) | s \big] \big] + \beta I^k \mathrm{E}\big[\gamma_1^*(\widetilde{x}_1) h_1(\widetilde{x}_1, \widetilde{a}_1, s_1) | s \big] \\
&\quad + \beta^2 \mathrm{E}\big[\varphi\big(\mu_1^*, \gamma_1^*(\widetilde{x}_1)\big) \omega\big(\ell(\widetilde{x}_1, \widetilde{a}_1, s_2), \varphi\big(\mu_1^*, \gamma_1^*(\widetilde{x}_1)\big), s_2\big) | s \big] && (49) \\
&= \mu \big[h_0(x, \widetilde{a}_0, s) + \beta I^k \mathrm{E}\big[h_0(\widetilde{x}_1, \widetilde{a}_1, s_1) + \beta \mathrm{E}\big[h_0\big(\widetilde{x}_2, a_2^*(\widetilde{x}_2), s_2\big) | s_1 \big] | s \big] \big] \\
&\quad + \gamma_0^* h_1(x, \widetilde{a}_0, s) + \beta \mathrm{E}\big[h_0(\widetilde{x}_1, \widetilde{a}_1, s_1) + \beta I^k \mathrm{E}\big[h_0\big(\widetilde{x}_2, a_2^*(\widetilde{x}_2), s_2\big) | s_1 \big] | s \big] \\
&\quad + \beta \mathrm{E} \gamma_1^*(\widetilde{x}_1) \big[h_1(\widetilde{x}_1, \widetilde{a}_1, s_1) + \beta \mathrm{E}\big[h_0\big(\widetilde{x}_2, a_2^*(\widetilde{x}_2), s_2\big) | s_1 \big] | s \big] \\
&\quad + \beta^2 I^k \mathrm{E}\big[\gamma_2^*(\widetilde{x}_2) h_1\big(\widetilde{x}_2, a_2^*(\widetilde{x}_2), s_2\big) | s \big] \\
&\quad + \beta^3 \mathrm{E} \varphi\big(\mu_2^*, \gamma_2^*(\widetilde{x}_2)\big) \big[\omega\big(\ell\big(\widetilde{x}_2, a_2^*(\widetilde{x}_2), s_3\big), \varphi\big(\mu_2^*, \gamma_2^*(\widetilde{x}_2)\big), s_3\big) | s \big] && (50) \\
&\quad \dots \\
&\geq A_T \equiv \mu \left[h_0(x, \widetilde{a}_0, s) + \beta I^k \mathrm{E}\left[\sum_{t=0}^{T-1} \beta^t h_0(\widetilde{x}_{t+1}, \widetilde{a}_{t+1}, s_{t+1}) | s \right] \right] \\
&\quad + \gamma_0^* \left[h_1(x, \widetilde{a}_0, s) + \beta \mathrm{E}\left[h_0(\widetilde{x}_1, \widetilde{a}_1, s_1) + I^k \sum_{t=1}^{T-1} \beta^t h_0(\widetilde{x}_{t+1}, \widetilde{a}_{t+1}, s_{t+1}) | s \right] \right] \\
&\quad + \beta \mathrm{E}\left[\gamma_1^*(\widetilde{x}_1) \left[h_1(\widetilde{x}_1, \widetilde{a}_1, s_1) + \beta \left[h_0(\widetilde{x}_2, \widetilde{a}_2, s_2) + I^k \sum_{t=2}^{T-1} \beta^{t-1} h_0(\widetilde{x}_{t+1}, \widetilde{a}_{t+1}, s_{t+1}) \right] \right] \Big| s \right] \\
&\quad \dots \\
&\quad + \beta^T \mathrm{E}\big[\gamma_T^*(\widetilde{x}_T) h_1(\widetilde{x}_T, \widetilde{a}_T, s_T) | s \big] \\
&\quad + \beta^{T+1} \mathrm{E}\big[\varphi\big(\mu_T^*, \gamma_T^*(\widetilde{x}_T)\big) \omega\big(\ell(\widetilde{x}_T, \widetilde{a}_T, s_{T+1}), \varphi\big(\mu_T^*, \gamma_T^*(\widetilde{x}_T)\big), s_{T+1}\big) | s \big], && (51)
\end{aligned}
$$

$$
\begin{aligned}
&\lim_{T \longrightarrow \infty} A_T \\
&= \mu \left[h_0(x, \widetilde{a}_0, s) + \beta I^k \mathrm{E}\left[\sum_{t=0}^{\infty} \beta^t h_0(\widetilde{x}_{t+1}, \widetilde{a}_{t+1}, s_{t+1}) | s \right] \right] \\
&\quad + \gamma_0^* \left[h_1(x, \widetilde{a}_0, s) + \beta \mathrm{E}\left[h_0(\widetilde{x}_1, \widetilde{a}_1, s_1) + I^k \sum_{t=1}^{T-1} \beta^t h_0(\widetilde{x}_{t+1}, \widetilde{a}_{t+1}, s_{t+1}) | s \right] \right] && (52)
\end{aligned}
$$

$$= \mu h_0(x, \widetilde{a}_0, s) + \gamma_0^* h_1(x, \widetilde{a}_0, s) + \beta \mathrm{E}\left[\sum_{j=0}^{l} \varphi^j(\mu, \gamma_0^*) \sum_{t=0}^{N_j} \beta^t h_0^j(\widetilde{x}_{t+1}, \widetilde{a}_{t+1}, s_{t+1})|s\right]. \tag{53}$$

In sum,

$$W(x, \mu, s) \geq \mu h_0(x, \widetilde{a}_0, s) + \gamma_0^* h_1(x, \widetilde{a}_0, s) + \beta \mathrm{E}\left[\sum_{j=0}^{l} \varphi^j(\mu, \gamma_0^*) \sum_{t=0}^{N_j} \beta^t h_0^j(\widetilde{x}_{t+1}, \widetilde{a}_{t+1}, s_{t+1})|s\right],$$

and, therefore, $W(x, \mu, s) = V_\mu(x, s)$. *Q.E.D.*

APPENDIX C: PROPERTIES OF VALUE FUNCTIONS AND SUPPORTING RESULTS ON SUBDIFFERENTIAL CALCULUS

Some Properties of $V_\mu(x, s)$ and **SPFE**

LEMMA 1A: *Assume* $\mathbf{PP}_\mu$ *has a solution at* (x, s) *with value* $V_\mu(x, s)$, *for* $x \in X$ *and* $\mu \in R_+^{l+1}$. *Then* (i) $V_\mu(x, s)$ *is convex and homogeneous of degree* 1 *in* μ, (ii) *if Assumptions* **A2–A4** *are satisfied*, $V_\mu(\cdot, s)$ *is continuous and uniformly bounded*, *and* (iii) *if Assumptions* **A5** *and* **A6** *are satisfied*, $V_\mu(\cdot, s)$ *is concave*.

PROOF: (i) To simplify notation, denote the solution of $\mathbf{PP}_\mu$ at (x, s) by $(\boldsymbol{a}_\mu^*, \gamma_\mu^*)$ and note that, by the definition of f, given any $\boldsymbol{a}, \mu, \mu' \in R_+^{l+1}$ and scalars λ, λ', we have

$$f_{(x,\lambda\mu+\lambda'\mu',s)}(\boldsymbol{a}) = \lambda f_{(x,\mu,s)}(\boldsymbol{a}) + \lambda' f_{(x,\mu',s)}(\boldsymbol{a}) \tag{54}$$

and, in particular, that $f_{(x,\lambda\mu,s)}(\boldsymbol{a}) = \lambda f_{(x,\mu,s)}(\boldsymbol{a})$.

To prove convexity, note that, given any $\mu, \mu' \in R_+^{l+1}$ and a scalar $\lambda \in (0, 1)$, we have

$$\begin{aligned} V_{\lambda\mu+(1-\lambda)\mu'}(x, s) &= \lambda f_{(x,\mu,s)}\left(\boldsymbol{a}_{\lambda\mu+(1-\lambda)\mu'}^*\right) + (1-\lambda) f_{(x,\mu',s)}\left(\boldsymbol{a}_{\lambda\mu+(1-\lambda)\mu'}^*\right) \\ &\leq \lambda f_{(x,\mu,s)}\left(\boldsymbol{a}_\mu^*\right) + (1-\lambda) f_{(x,\mu',s)}\left(\boldsymbol{a}_{\mu'}^*\right) \\ &= \lambda V_\mu(x, s) + (1-\lambda) V_{\mu'}(x, s), \end{aligned}$$

where the first equality follows from (54) and the inequality follows from the fact that $\boldsymbol{a}_\mu^*$ and $\boldsymbol{a}_{\mu'}^*$ maximize $\mathbf{SPP}_\mu$ and $\mathbf{SPP}_{\mu'}$, respectively.

To prove homogeneity of degree 1, fix a scalar $\lambda > 0$. Then, using (54) and the fact that $\boldsymbol{a}_{\lambda\mu}^*$ and $\boldsymbol{a}_\mu^*$ are maximal elements attaining $V_{\lambda\mu}(x, s)$ and $V_\mu(x, s)$, respectively:

$$\begin{aligned} V_{\lambda\mu}(x, , s) &= f_{(x,\lambda\mu,s)}\left(\boldsymbol{a}_{\lambda\mu}^*\right) \geq f_{(x,\lambda\mu,s)}\left(\boldsymbol{a}_\mu^*\right) \\ &= \lambda f_{(x,\mu,s)}\left(\boldsymbol{a}_\mu^*\right) = \lambda V_\mu(x, s) \geq \lambda f_{(x,\mu,s)}\left(\boldsymbol{a}_{\lambda\mu}^*\right) \\ &= f_{(x,\lambda\mu,s)}\left(\boldsymbol{a}_{\lambda\mu}^*\right) = V_{\lambda\mu}(x, s). \end{aligned}$$

The proofs of (ii) and (iii) are straightforward: in particular, (ii) follows from applying the theorem of the maximum (Stokey, Lucas, and Prescott (1989, Theorem 3.6)) and

(iii) follows from the fact that the constraint sets are convex and the objective function concave. *Q.E.D.*

LEMMA 2A: *If the* saddle-point problem **SPFE** *at* (x, μ, s), *has a solution*, *its value is unique*.

PROOF: It is a standard argument: consider two solutions to the right-hand side of **SPFE** at (x, μ, s), $(\widetilde{a}, \widetilde{\gamma})$ and $(\widehat{a}, \widehat{\gamma})$. Then, by repeated application of the saddle-point min and max conditions:

$$\begin{aligned}
&\mu h_0(x, \widetilde{a}, s) + \widetilde{\gamma} h_1(x, \widetilde{a}, s) + \beta \mathrm{E}\big[W\big(\ell\big(x, \widetilde{a}, s'\big), \varphi(\mu, \widetilde{\gamma}), s'\big)|s\big] \\
&\quad \geq \mu h_0(x, \widehat{a}, s) + \widetilde{\gamma} h_1(x, \widehat{a}, s) + \beta \mathrm{E}\big[W\big(\ell\big(x, \widehat{a}, s'\big), \varphi(\mu, \widetilde{\gamma}), s'\big)|s\big] \\
&\quad \geq \mu h_0(x, \widehat{a}, s) + \widehat{\gamma} h_1(x, \widehat{a}, s) + \beta \mathrm{E}\big[W\big(\ell\big(x, \widehat{a}, s'\big), \varphi(\mu, \widehat{\gamma}), s'\big)|s\big] \\
&\quad \geq \mu h_0(x, \widetilde{a}, s) + \widehat{\gamma} h_1(x, \widetilde{a}, s) + \beta \mathrm{E}\big[W\big(\ell\big(x, \widetilde{a}, s'\big), \varphi(\mu, \widehat{\gamma}), s'\big)|s\big] \\
&\quad \geq \mu h_0(x, \widetilde{a}, s) + \widetilde{\gamma} h_1(x, \widetilde{a}, s) + \beta \mathrm{E}\big[W\big(\ell\big(x, \widetilde{a}, s'\big), \varphi(\mu, \widetilde{\gamma}), s'\big)|s\big].
\end{aligned}$$

Therefore, the value of the objective at both $(\widetilde{a}, \widetilde{\gamma})$ and $(\widehat{a}, \widehat{\gamma})$ coincides. *Q.E.D.*

Properties of Convex Homogeneous Functions

To simplify the exposition of these properties, let $F : R^m_+ \to R$ be continuous and convex, satisfying $F(x) < \infty$ for some $x \gg 0$. The *subdifferential set* of F at y, denoted $\partial F(y)$, is given by

$$\partial F(y) = \big\{z \in R^m \mid F\big(y'\big) \geq F(y) + \big(y' - y\big)z \text{ for all } y' \in R^m_+\big\}.$$

The following *facts*, regarding F, support our discussion on "uniqueness and sufficiency without differentiability" in Section 3 and, in particular, are used in proving Lemma 1 and Lemma 5A (below):

F1. (i) $\partial F(y)$ is a closed and convex set; (ii) if $y \in R^m_{++}$, $\partial F(y)$ is also non-empty and bounded, and (iii) the correspondence $\partial F : R^m_+ \longrightarrow R^m$ is upper hemicontinuous.

F2. F is differentiable at y if, and only if, $\partial F(y)$ consists of a single vector; that is, $\partial F(y) = \{\nabla F(y)\}$, where $\nabla F(y)$ is called the *gradient* of F at y.

F3.

LEMMA 3A—Euler's formula: *If F is also homogeneous of degree* 1 *and $z \in \partial F(y)$, then $F(y) = yz$. Furthermore, for any $\lambda > 0$, $\partial F(\lambda y) = \partial F(y)$, that is, the subdifferential is homogeneous of degree* 0.

F4.

LEMMA 4A—Kuhn–Tucker: x^* *minimizes F on R^m_+* if and only if *there is a $f(x^*) \in \partial F(x^*)$ such that*: (i) $f(x^*) \geq 0$, *and* (ii) $x^* f(x^*) = 0$.

F5. If $F = \sum_{i=1}^m \alpha_i F^i$, where, for $i = 1, \dots, m$, $\alpha_i > 0$ and $F^i : R^m_+ \to R$ is convex, then $\partial F(y) = \sum_{i=1}^m \alpha_i \partial F^i(y)$.

Facts **F1** and **F2** are well known and can be found in Rockafellar (1970): **F1**(i) follows immediately from the definition of the subdifferential (Chapter 23); **F1**(ii) from Theorem 23.4; **F1**(iii) from Theorem 24.4, and **F2** from Theorem 25.1. Similarly, Fact **F5** follows from Theorem 23.8.

PROOF OF LEMMA 3A: Let $z \in \partial F(y)$. Then, for any $\lambda > 0$, $F(\lambda y) - F(y) \geq (\lambda y - y)z$, and, by homogeneity of degree 1, $(\lambda - 1)F(y) \geq (\lambda - 1)yz$. If $\lambda > 1$, this weak inequality results in $F(y) \geq yz$, while if $\lambda \in (0, 1)$, it results in $F(y) \leq yz$. Therefore, $F(y) = yz$. To see that $\partial F(y)$ is homogeneous of degree zero, note that, for any $\lambda > 0$,

$$\begin{aligned}\partial F(\lambda y) &= \{z \in R^m \mid F(y') \geq F(\lambda y) + (y' - \lambda y)z \text{ for all } y' \in R^m_+\} \\ &= \{z \in R^m \mid F(\lambda y'') \geq F(\lambda y) + (\lambda y'' - \lambda y)z \text{ for all } y'' \in R^m_+\} \\ &= \{z \in R^m \mid F(y'') \geq F(y) + (y'' - y)z \text{ for all } y'' \in R^m_+\} \\ &= \partial F(y). \qquad\qquad Q.E.D.\end{aligned}$$

PROOF OF LEMMA 4A: The proof is based on Rockafellar's (1981, Chapter 5) characterization of stationary points using subdifferential calculus (R81 in what follows). First, we prove *necessity*: let x^* minimize F on R^m_+. Since the constrained set is convex with a non-empty interior, x^* minimizes $F(x) - \lambda^* x$, where $\lambda^* \in R^m_+$ and $\lambda^{*j} = 0$ if $x^{*j} > 0$; otherwise x^* would not be a minimizer. By R81, Proposition 5A, $0 \in \partial\{F(x) - \lambda^* x\}$ and, since $\{x \in R^m_{++} | F(x) < \infty\} \neq \emptyset$, $\partial\{F(x) - \lambda^* x\} = \partial F(x) + \partial\{-\lambda^* x\}$ (R81, Theorem 5C); that is, there exists $f(x^*) \in \partial F(x^*)$ such that $f(x^*) - \lambda^* = 0$. Therefore, $f(x^*) \geq 0$ and $x^* f(x^*) - \lambda^* x^* = x^* f(x^*) = 0$.

To see *sufficiency*, note that since F is convex and $f(x^*) \in \partial F(x^*)$, for any $x \in R^m_+$, $F(x) - F(x^*) \geq (x - x^*) f(x^*)$, but given (i) and (ii), the inequality simplifies to $F(x) - F(x^*) \geq 0$. *Q.E.D.*

Sufficiency (Without Differentiability): Supporting Results

LEMMA 5A: *Let W be continuous in (x, μ) and convex and homogeneous of degree 1 in μ, for every s.*

(i) *If $W(x, \mu, s)$ is finite, $\partial_\mu W(x, \mu, s) \neq \emptyset$ and if $\omega(x, \mu, s) \in \partial_\mu W(x, \mu, s)$, then $W(x, \mu, s) = \mu\omega(x, \mu, s)$ and, for all $\lambda > 0$, $\omega(x, \mu, s) \in \partial_\mu W(x, \lambda\mu, s)$. Furthermore, W is differentiable in μ at (x, μ, s) if, and only if, $\partial_\mu W(x, \mu, s)$ is a singleton.*

(ii) $(a^*, \gamma^*) \in \Psi_W(x, \mu, s)$ if and only if, *for all s' reached from s, there is a $\omega(x^{*\prime}, \mu^{*\prime}, s') \in \partial_\mu W(x^{*\prime}, \mu^{*\prime}, s')$ with $x^{*\prime} = \ell(x, a^*, s')$ and $\mu^{*\prime} = \varphi(\mu, \gamma^*)$, such that*

$$\begin{aligned}&\mu h_0(x, a^*, s) + \gamma^* h_1(x, a^*, s) + \beta \mathrm{E}[\varphi(\mu, \gamma^*)\omega(x^{*\prime}, \varphi(\mu, \gamma^*), s')|s] \\ &\quad \geq \mu h_0(x, a, s) + \gamma^* h_1(x, a, s) + \beta \mathrm{E}[\varphi(\mu, \gamma^*)\omega(x', \varphi(\mu, \gamma^*), s')|s],\end{aligned} \tag{55}$$

for all $a \in A$ and $x' = \ell(x, a, s')$ satisfying $p(x, a, s) \geq 0$, and, for $j = 0, \ldots, l$,

$$h_1^j(x, a^*, s) + \beta \mathrm{E}[\omega^j(x^{*\prime}, \varphi(\mu, \gamma^*), s')|s] \geq 0, \tag{56}$$

$$\gamma^{*j}[h_1^j(x, a^*, s) + \beta \mathrm{E}[\omega^j(x^{*\prime}, \varphi(\mu, \gamma^*), s')|s]] = 0. \tag{57}$$

PROOF: Part (i) follows from Facts **F1–F3**. In particular, **F3** implies that if $z \in \partial F(y)$, then $z \in \partial F(\lambda y)$. The saddle-point max inequality condition of part (ii) (55) is the same as the max saddle-point condition of **SPFE** expressed with its Euler representation. Since by (i) W always has at least one Euler representation, the proof of (55) is immediate. To see the min inequality of part (ii), begin by rewriting the first inequality of $\Psi_W(x, \mu, s)$, (19), as

$$\gamma h_1(x, a^*, s) + \beta \mathrm{E}\big[W\big(\ell(x, a^*, s'), \varphi(\mu, \gamma), s'\big)|s\big]$$
$$\geq \gamma^* h_1(x, a^*, s) + \beta \mathrm{E}\big[W\big(\ell(x, a^*, s'), \varphi(\mu, \gamma^*), s'\big)|s\big].$$

Then, let

$$F_{(x,a^*,\mu,s)}(\gamma) = \gamma h_1(x, a^*, s) + \beta \mathrm{E}\big[W\big(x^{*\prime}, \varphi(\mu, \gamma), s'\big)|s\big].$$

By Fact **F5,**

$$\partial F_{(x,a^*,\mu,s)}(\gamma) = h_1(x, a^*, s) + \beta \mathrm{E}\big[\partial_\mu W\big(x^{*\prime}, \varphi(\mu, \gamma), s'\big)|s\big],$$

and it follows from **F4** (Lemma 4A) that the Kuhn–Tucker conditions (56) and (57) are necessary and sufficient. *Q.E.D.*

APPENDIX D: PROOF OF THEOREM 3

The proof of Theorem 3(i) is based on the following two lemmas and Kakutani's fixed point theorem.

LEMMA 6A: *Assume* **A4** *and that* $W \in \mathcal{M}_{bc}$ *satisfies* **SIC**. *There exists a* $C > 0$ *such that if* $(a^*, \gamma^*) \in \Psi_W(x, \mu, s)$, *then* $\|\gamma^*\| \leq C\|\mu\|$.

Before we prove Lemma 6A, note that condition **SIC** implies the following condition, which is a version of *Karlin's condition*:[42]

SK. W, with $W = \mu\omega$, satisfies the *interiority condition* if there exists an $\epsilon > 0$, such that for any $(x, s) \in X \times S$, $\mu \in R_+^{l+1}$, and $\gamma \in R_+^{l+1}$, $\gamma \neq 0$, there exists $\widetilde{a} \in A$, satisfying $p(x, \widetilde{a}, s) > 0$, and $\gamma[h_1(x, \widetilde{a}, s) + \beta \mathrm{E}[\omega(\ell(x, \widetilde{a}, s'), \mu, s')|s]] \geq \epsilon$.

PROOF: Lemma 6A is trivially satisfied if $\gamma^* = 0$; therefore, let $(a^*, \gamma^*) \in \Psi_W(x, \mu, s)$ with $\gamma^* \neq 0$ and the Euler representations $W(\ell(x, a^*, s'), \varphi(\mu, \gamma^*), s') = \mu'^* \omega(x'^*, \mu'^*, s')$, and let $\widetilde{a} \in B(x, s)$ be the interior allocation of the **SIC** condition. Using the notation of Section 3 (Footnote 26), the slackness condition $\gamma^*[h_1(x, a^*, s) + \beta \mathrm{E}[\omega(x'^*, \mu'^*, s')|s]] = 0$, and **SIC,** the max inequality can be expressed as

$$\mu\big[h_0(x, a^*, s) + \beta \mathrm{E}\big[I^k \omega\big(x'^*, \mu'^*, s'\big)|s\big] - \big(h_0(x, \widetilde{a}, s) + \beta \mathrm{E}\big[I^k \omega\big(\ell(x, \widetilde{a}, s'), \mu'^*, s'\big)|s\big]\big)\big]$$
$$\geq \gamma^*\big[h_1(x, \widetilde{a}, s) + \beta \mathrm{E}\big[\omega\big(\ell(x, \widetilde{a}, s'), \mu'^*, s'\big)|s\big]\big] \geq \varepsilon\|\gamma^*\|.$$

If there is no uniform bound, then, for any $\delta > 0$, there is a Kuhn–Tucker multiplier γ^* such that $\delta\|\gamma^*\| \geq \|\mu\|$, but in this case it must be that

$$\delta \frac{\mu}{\|\mu\|}\big[h_0(x, a^*, s) + \beta \mathrm{E}\big[I^k \omega\big(x'^*, \mu'^*, s'\big)|s\big]$$
$$- \big(h_0(x, \widetilde{a}, s) + \beta \mathrm{E}\big[I^k \omega\big(\ell(x, \widetilde{a}, s'), \mu'^*, s'\big)|s\big]\big)\big]$$
$$\geq \frac{\mu}{\|\gamma^*\|}\big[h_0(x, a^*, s) + \beta \mathrm{E}\big[\omega^j\big(\ell(x, a^*, s'), \mu'^*, s'\big)|s\big]$$

[42]See Takayama (1985).

$$
\begin{aligned}
&- \left(h_0(x,\widetilde{a},s) + \beta \mathrm{E}\left[I^k \omega\left(\ell(x,\widetilde{a},s'),\mu'^*,s'\right)|s\right]\right)\Big] \\
&\geq \frac{\gamma^*}{\|\gamma^*\|}\left[h_1(x,\widetilde{a},s) + \beta \mathrm{E}\left[\omega\left(\ell(x,\widetilde{a},s'),\mu'^*,s'\right)|s\right]\right] \geq \varepsilon,
\end{aligned}
$$

which, by **SIC**, is not possible for δ small enough, since all the terms in the main brackets are bounded. Therefore, there exists a $C > 0$ such that $\|\gamma^*\| \leq C\|\mu\|$.

The next lemma requires some additional notation. Let $B(x,s) = \{a \in A : p(x,a,s) \geq 0\}$, and $G(\mu) = \{\gamma \in R_+^{l+1} : \|\gamma\| \leq C\|\mu\|\}$, where $\|\mu\| > 0$. Define

$$
\begin{aligned}
&\mathrm{SP}^a_{W(x,\mu,s)}(\gamma) \\
&\quad = \left\{ \begin{array}{c} a \in B(x,s) : \mu h_0(x,a,s) + \gamma h_1(x,a,s) + \beta \mathrm{E}\left[W\left(\ell(x,a,s'),\varphi(\mu,\gamma),s'\right)|s\right] \\ \geq \mu h_0(x,\widetilde{a},s) + \gamma h_1(x,\widetilde{a},s) + \beta \mathrm{E}\left[W\left(\ell(x,\widetilde{a},s'),\varphi(\mu,\gamma),s'\right)|s\right], \forall \widetilde{a} \in B(x,s) \end{array} \right\}, \\
&\mathrm{SP}^\gamma_{W(x,\mu,s)}(a) \\
&\quad = \left\{ \begin{array}{c} \gamma \in G(\mu) : \mu h_0(x,a,s) + \gamma h_1(x,a,s) + \beta \mathrm{E}\left[W\left(\ell(x,a,s'),\varphi(\mu,\gamma),s'\right)|s\right] \\ \leq \mu h_0(x,a,s) + \widetilde{\gamma} h_1(x,a,s) + \beta \mathrm{E}\left[W\left(\ell(x,a,s'),\varphi(\mu,\widetilde{\gamma}),s'\right)|s\right], \forall \widetilde{\gamma} \in G(\mu) \end{array} \right\},
\end{aligned}
$$

and $\mathrm{SP}_{W(x,\mu,s)} : B(x,s) \times G(\mu) \to B(x,s) \times G(\mu)$ by $\mathrm{SP}_{W(x,\mu,s)}(a,\gamma) = (\mathrm{SP}^a_{W(x,\mu,s)}(\gamma), \mathrm{SP}^\gamma_{W(x,\mu,s)}(a))$. *Q.E.D.*

LEMMA 7A: *Assume* **A1–A5** *and that* $W \in \mathcal{M}_{bc}$ *satisfies* **SIC**. *The correspondence* $\mathrm{SP}_{W(x,\mu,s)}$ *is non-empty, convex-valued, and upper hemicontinuous.*

PROOF: $\mathrm{SP}_{W(x,\mu,s)}$ is a max and min problem of continuous functions on compact sets with non-empty interiors and, therefore, for all $(a,\gamma) \in B(x,s) \times G(\mu)$ is non-empty and, given our concavity assumptions, it is convex-valued. To see that it is upper hemicontinuous, let $(a_n,\gamma_n) \to (a,\gamma)$ with $a_n \in \mathrm{SP}^a_{W(x,\mu,s)}(\gamma_n)$ and $\gamma_n \in \mathrm{SP}^\gamma_{W(x,\mu,s)}(a_n)$—that is, for all $\widetilde{a} \in B(x,s)$, $a_n \succsim \widetilde{a}$, and for all $\widetilde{\gamma} \in G(\mu)$, $\gamma_n \precsim \widetilde{\gamma}$, for all n, but, by continuity of the implied functions, $a \succsim \widetilde{a}$ and $\gamma \precsim \widetilde{\gamma}$, therefore $(a,\gamma) \in \mathrm{SP}_{W(x,\mu,s)}(a,\gamma)$. *Q.E.D.*

PROOF OF THEOREM 3(I): The assumptions of Lemmas 6A and 7A are also assumed in Theorem 3(i); therefore, the correspondence $\mathrm{SP}_{W(x,\mu,s)} : B(x,s) \times G(\mu) \to B(x,s) \times G(\mu)$ mapping non-empty, convex, and compact sets to themselves, is non-empty, convex-valued, and upper hemicontinuous, and by Kakutani's fixed point theorem (e.g., Mas-Colell, Whinston, and Green (1995)), there exists $(a^*,\gamma^*) \in \mathrm{SP}_{W(x,\mu,s)}(a^*,\gamma^*)$. Finally, that a^* is unique when $W \in \mathcal{M}_{bc}$ and Assumption **A6s** is satisfied, is a standard result (see footnote 23). *Q.E.D.*

Before we prove Theorem 3(ii), note that, given the assumptions of Theorem 3, $(a^*,\gamma^*) \in \mathrm{SP}_{W(x,\mu,s)}(a^*,\gamma^*)$ if and only if $(a^*,\gamma^*) \in \Psi_W(x,\mu,s)$. If $(a^*,\gamma^*) \in \mathrm{SP}_{W(x,\mu,s)}(a^*,\gamma^*)$, then (a^*,γ^*) satisfies inequalities (19)–(20), with the former restricted to $G(\mu)$, but by Lemma 6A this restriction is not binding once **SIC** is assumed. Conversely, if $(a^*,\gamma^*) \in \Psi_W(x,\mu,s)$, then $a^* \in \mathrm{SP}^a_{W(x,\mu,s)}(\gamma^*)$ and $\gamma^* \in \mathrm{SP}^\gamma_{W(x,\mu,s)}(a^*)$. Obviously, only when saddle-point solutions are unique—that is, $(a^*,\gamma^*) = \psi_W(x,\mu,s)$—we have $\psi_W(x,\mu,s) = \mathrm{SP}_{W(x,\mu,s)}(a^*,\gamma^*) = (a^*,\gamma^*)$.

PROOF OF THEOREM 3(II): First we show that, given $W \in \mathcal{M}$, $T^*W(\cdot,\cdot,s)$ is also continuous by extending the *theorem of the maximum* to *saddle-points.* That $\mathrm{SP}_{W(x,\mu,s)}$ satisfies the closed-graph property (Lemma 7A) implies that $\Psi_W(x,\mu,s) \subset B(x,s) \times G(\mu)$

is closed. Furthermore, $B(\cdot, s) : X \longrightarrow A$ and $G(\cdot)$: $R_+^{l+1} \to R_+^{l+1}$ are continuous correspondences. Now, to show that Ψ_W is an upper hemicontinuous correspondence, fix (x, μ) and let the sequence $(x_n, \mu_n) \to (x, \mu)$ and $(a_n^*, \gamma_n^*) \in \Psi_W(x_n, \mu_n, s)$, for all n. Since $B(\cdot, s)$ and $G(\cdot)$ are upper hemicontinuous, there exists a subsequence $(a_{n_k}^*, \gamma_{n_k}^*) \to (a^*, \gamma^*) \in B(x, s) \times G(\mu)$ with $(a_{n_k}^*, \gamma_{n_k}^*) \in \Psi_W(x_{n_k}, \mu_n, s)$. Given an arbitrary $(\widehat{a}, \widehat{\gamma}) \in B(x, s) \times G(\mu)$, since $B(\cdot, s)$ and $G(\cdot)$ are lower hemicontinuous, there exists a subsequence $(\widehat{a}_{n_k}, \widehat{\gamma}_{n_k}) \to (\widehat{a}, \widehat{\gamma})$ with $(\widehat{a}_{n_k}, \widehat{\gamma}_{n_k}) \in B(x_{n_k}, s) \times G(\mu_{n_k})$; that is,

$$\begin{aligned}
&\mu_{n_k} h_0\big(x_{n_k}, a_{n_k}^*, s\big) + \widehat{\gamma}_{n_k} h_1\big(x_{n_k}, a_{n_k}^*, s\big) + \beta \mathrm{E}\big[W\big(\ell\big(x_{n_k}, a_{n_k}^*, s'\big), \varphi(\mu_{n_k}, \widehat{\gamma}_{n_k}), s'\big)|s\big] \\
&\quad \geq \mu_{n_k} h_0\big(x_{n_k}, a_{n_k}^*, s\big) + \gamma_{n_k}^* h_1\big(x_{n_k}, a_{n_k}^*, s\big) + \beta \mathrm{E}\big[W\big(\ell\big(x_{n_k}, a_{n_k}^*, s'\big), \varphi\big(\mu_{n_k}, \gamma_{n_k}^*\big), s'\big)|s\big] \\
&\quad \geq \mu_{n_k} h_0(x_{n_k}, \widehat{a}_{n_k}, s) + \gamma_{n_k}^* h_1(x_{n_k}, \widehat{a}_{n_k}, s) + \beta \mathrm{E}\big[W\big(\ell\big(x_{n_k}, \widehat{a}_{n_k}, s'\big), \varphi\big(\mu_{n_k}, \gamma_{n_k}^*\big), s'\big)|s\big],
\end{aligned}$$

and by continuity,

$$\begin{aligned}
&\mu h_0\big(x, a^*, s\big) + \widehat{\gamma} h_1\big(x, a^*, s\big) + \beta \mathrm{E}\big[W\big(\ell\big(x, a^*, s'\big), \varphi(\mu, \widehat{\gamma}), s'\big)|s\big] \\
&\quad \geq \mu h_0\big(x, a^*, s\big) + \gamma^* h_1\big(x, a^*, s\big) + \beta \mathrm{E}\big[W\big(\ell\big(x, a^*, s'\big), \varphi\big(\mu, \gamma^*\big), s'\big)|s\big] \\
&\quad \geq \mu h_0(x, \widehat{a}, s) + \gamma^* h_1(x, \widehat{a}, s) + \beta \mathrm{E}\big[W\big(\ell\big(x, \widehat{a}, s'\big), \varphi\big(\mu, \gamma^*\big), s'\big)|s\big],
\end{aligned}$$

therefore $(a^*, \gamma^*) \in \Psi_W(x, \mu, s)$. Now we can show that $T^*W(\cdot, \cdot, s)$ is continuous. Again let the sequence $(x_n, \mu_n) \to (x, \mu)$ and $(a_n^*, \gamma_n^*) \in \Psi_W(x_n, \mu_n, s)$, for all n; then,

$$\begin{aligned}
T^*W(x_n, \mu_n, s) &= \mu_n\big[h_0\big(x_n, a_n^*, s\big) + \beta \mathrm{E}\big[I^k \omega\big(\ell\big(x_n, a_n^*, s'\big), \varphi\big(\mu_n, \gamma_n^*\big), s'\big)|s\big]\big] \\
&\quad + \gamma_n^*\big[h_1\big(x_n, a_n^*, s\big) + \beta \mathrm{E}\big[\omega\big(\ell\big(x_n, a_n^*, s'\big), \varphi\big(\mu_n, \gamma_n^*\big), s'\big)|s\big]\big] \\
&= \mu_n\big[h_0\big(x_n, a_n^*, s\big) + \beta \mathrm{E}\big[I^k \omega\big(\ell\big(x_n, a_n^*, s'\big), \varphi\big(\mu_n, \gamma_n^*\big), s'\big)|s\big]\big].
\end{aligned}$$

Since the last equality is satisfied for every sequence and subsequence, we only need to consider the last term. In particular, if we let $\overline{W} = \limsup T^*W(x_n, \mu_n, s)$ and $\underline{W} = \liminf T^*W(x_n, \mu_n, s)$, then there is a subsequence $\{x_{n_k}, \mu_{n_k}\}$ such that

$$\overline{W} = \lim \mu_{n_k}\big[h_0\big(x_{n_k}, a_{n_k}^*, s\big) + \beta \mathrm{E}\big[I^k \omega\big(\ell\big(x_{n_k}, a_{n_k}^*, s'\big), \varphi\big(\mu_{n_k}, \gamma_{n_k}^*\big), s'\big)|s\big]\big]$$

and, by the upper hemicontinuity of Ψ_W, there is a further subsequence $(a_{n_{k_r}}^*, \gamma_{n_{k_r}}^*) \in \Psi_W(x_{n_{k_r}}, \mu_{n_{k_r}}, s)$ converging to $(a^*, \gamma^*) \in \Psi_W(x, \mu, s)$; therefore, $\overline{W} = \lim T^*W(x_{n_{k_r}}, \mu_{n_{k_r}}, s) = T^*W(x, \mu, s)$. Since the same argument applies to $\underline{W}$, it follows that $T^*W(x_n, \mu_n, s) \to T^*W(x, \mu, s)$. We now show that the remaining properties of $\mathcal{M}$ are preserved.

That T^*W is also bounded follows from Assumptions **A3–A4** and the boundedness condition on W. Furthermore, by Assumption **A1b**, T^*W is measurable; therefore, it satisfies (i) of the definition of $\mathcal{M}_b$. To see that T^*W is homogeneous of degree 1 (i.e., $T^*W(x, \lambda\mu, s) = \lambda T^*W(x, \mu, s)$, for any $\lambda > 0$), let (a^*, γ^*) be a solution to the saddle-point Bellman equation at (x, μ, s)—that is, $(a^*, \gamma^*) \in \Psi_W(x, \mu, s)$. It is enough to show that, for any $\lambda > 0$, $(a^*, \lambda\gamma^*) \in \Psi_W(x, \lambda\mu, s)$—that is, $\gamma^*(x, \lambda\mu, s) = \lambda\gamma^*(x, \mu, s)$—since

$$\lambda\big(T^*W\big)(x, \mu, s) = \lambda\big[\mu h_0\big(x, a^*, s\big) + \gamma^* h_1\big(x, a^*, s\big) + \beta \mathrm{E} W\big(x^{*\prime}, \varphi\big(\mu, \gamma^*\big), s'\big)\big],$$

and $W(x^{*\prime}, \varphi(\lambda\mu, \lambda\gamma^*), s') = \lambda W(x^{*\prime}, \varphi(\mu, \gamma^*), s')$. For any $\gamma \geq 0$, let $\gamma_\lambda \equiv \gamma\lambda^{-1}$; then, for any $a \in A(x, s)$ (resulting in $x' = \ell(x, a, s')$) and $\gamma \geq 0$,

$$\lambda\mu h_0\big(x, a^*, s\big) + \gamma h_1\big(x, a^*, s\big) + \beta \mathrm{E} W\big(x^{*\prime}, \varphi(\lambda\mu, \gamma), s'\big)$$

$$\equiv \lambda\mu h_0(x, a^*, s) + \lambda\gamma_\lambda h_1(x, a^*, s) + \beta \mathrm{E} W(x^{*\prime}, \varphi(\lambda\mu, \lambda\gamma_\lambda), s')$$
$$= \lambda[\mu h_0(x, a^*, s) + \gamma_\lambda h_1(x, a^*, s) + \beta \mathrm{E} W(x^{*\prime}, \varphi(\mu, \gamma_\lambda), s')]$$
$$\geq \lambda[\mu h_0(x, a^*, s) + \gamma^*(x, \mu, s) h_1(x, a^*, s) + \beta \mathrm{E} W(x^{*\prime}, \varphi(\mu, \gamma^*(x, \mu, s)), s')]$$
$$= \lambda\mu h_0(x, a^*, s) + \gamma^*(x, \lambda\mu, s) h_1(x, a^*, s) + \beta \mathrm{E} W(x^{*\prime}, \varphi(\lambda\mu, \gamma^*(x, \lambda\mu, s)), s')$$
$$\geq \lambda[\mu h_0(x, a, s) + \gamma^*(x, \mu, s) h_1(x, a, s) + \beta \mathrm{E} W(x', \varphi(\mu, \gamma^*(x, \mu, s)), s')]$$
$$= \lambda\mu h_0(x, a, s) + \gamma^*(x, \lambda\mu, s) h_1(x, a, s) + \beta \mathrm{E} W(x', \varphi(\lambda\mu, \gamma^*(x, \lambda\mu, s)), s').$$

The three equalities follow from the above definitions and the fact that W is homogeneous of degree 1 in μ, while the two inequalities follow from the fact that $(a^*, \gamma^*(x, \mu, s)) \in \Psi_{(T^*W)}(x, \mu, s)$. This shows that $(a^*, \gamma^*(x, \lambda\mu, s)) \in \Psi_{(T^*W)}(x, \lambda\mu, s)$ and, in fact, the second equality shows that $(T^*W)(x, \lambda\mu, s) = \lambda(T^*W)(x, \mu, s)$.

To show that T^*W is convex, choose arbitrary $\alpha \in (0, 1)$, μ, $\widetilde{\mu}$, in R_+^{l+1} and (x, s). Let $\mu_\alpha \equiv \alpha\mu + (1-\alpha)\widetilde{\mu}$, $(a_\alpha^*, \gamma_\alpha^*) \in \Psi_{(T^*W)}(x, \mu_\alpha, s)$, $x_\alpha^{*\prime} = \ell(x, a_\alpha^*, s')$, and $(a^*, \gamma^*) \in \Psi_{(T^*W)}(x, \mu, s)$, $x^{*\prime} = \ell(x, a^*, s')(\widetilde{a}^*, \widetilde{\gamma}^*) \in \Psi_{(T^*W)}(x, \widetilde{\mu}, s)$, $\widetilde{x}^{*\prime} = \ell(x, \widetilde{a}^*, s')$, and $\widetilde{\gamma}_\alpha^* = \alpha\gamma^* + (1-\alpha)\widetilde{\gamma}^*$; then

$$(T^*W)(x, \mu_\alpha, s)$$
$$= \mu_\alpha h_0(x, a_\alpha^*, s) + \gamma_\alpha^* h_1(x, a_\alpha^*, s) + \beta \mathrm{E}[W(x_\alpha^{*\prime}, \varphi(\mu_\alpha, \gamma_\alpha^*), s')|s]$$
$$\leq \mu_\alpha h_0(x, a_\alpha^*, s) + \widetilde{\gamma}_\alpha^* h_1(x, a_\alpha^*, s) + \beta \mathrm{E}[W(x_\alpha^{*\prime}, \varphi(\mu_\alpha, \widetilde{\gamma}_\alpha^*), s')|s]$$
$$\leq \mu_\alpha h_0(x, a_\alpha^*, s) + \widetilde{\gamma}_\alpha^* h_1(x, a_\alpha^*, s) + \beta \mathrm{E}[\alpha W(x_\alpha^{*\prime}, \varphi(\mu, \gamma^*), s')$$
$$+ (1-\alpha) W(x_\alpha^{*\prime}, \varphi(\widetilde{\mu}, \widetilde{\gamma}^*), s')|s]$$
$$= \alpha[\mu h_0(x, a_\alpha^*, s) + \gamma^* h_1(x, a_\alpha^*, s) + \beta \mathrm{E} W(x_\alpha^{*\prime}, \varphi(\mu, \gamma^*), s')]$$
$$+ (1-\alpha)[\widetilde{\mu} h_0(x, a_\alpha^*, s) + \widetilde{\gamma}^* h_1(x, a_\alpha^*, s) + \beta \mathrm{E} W(x_\alpha^{*\prime}, \varphi(\widetilde{\mu}, \widetilde{\gamma}^*), s')]$$
$$\leq \alpha[\mu h_0(x, a^*, s) + \gamma^* h_1(x, a^*, s) + \beta \mathrm{E} W(x^{*\prime}, \varphi(\mu, \gamma^*), s')]$$
$$+ (1-\alpha)[\widetilde{\mu} h_0(x, \widetilde{a}^*, s) + \widetilde{\gamma}^* h_1(x, \widetilde{a}^*, s) + \beta \mathrm{E} W(\widetilde{x}^{*\prime}, \varphi(\widetilde{\mu}, \widetilde{\gamma}^*), s')]$$
$$= \alpha(T^*W)(x, \mu, s) + (1-\alpha)(T^*W)(x, \widetilde{\mu}, s),$$

where the first inequality follows from the fact that γ_α^* is a minimizer at (x, μ_α, s), the second from the convexity of W, and the third from the maximality of a^* and $\widetilde{a}^*$ at (x, μ, s) and $(x, \widetilde{\mu}, s)$ respectively. *Q.E.D.*

PROOF OF THEOREM 3(III): This is just an application of *Blackwell's sufficiency conditions for a contraction* (e.g., Stokey, Lucas, and Prescott (1989, Theorem 3.3)). The following Lemmas 8A–10A show that T^* satisfies the conditions of the *contraction mapping theorem* and *Blackwell's sufficiency conditions*. *Q.E.D.*

LEMMA 8A: *$\mathcal{M}$ is a non-empty complete metric space* (*recall that $\mathcal{M}$ denotes either $\mathcal{M}_b$ or $\mathcal{M}_{bc}$*).

PROOF: It follows from the definition of $\mathcal{M}$ that it is non-empty. Without accounting for the homogeneity property, it follows from standard arguments (see, e.g., Stokey, Lucas, and Prescott (1989, Theorem 3.1)) that every Cauchy sequence $\{W^n\} \in \mathcal{M}$ converges to $W \in \mathcal{M}$ satisfying (i) and the convexity property (ii) (and (iii) if $W \in \mathcal{M}_{bc}$). To see that the homogeneity property is also satisfied, note that for any (x, μ, s) and $\lambda > 0$,

$$\begin{aligned}
&\left|W(x, \lambda\mu, s) - \lambda W(x, \mu, s)\right| \\
&\quad = \left|W(x, \lambda\mu, s) - W^n(x, \lambda\mu, s) + \lambda W^n(x, \mu, s) - \lambda W(x, \mu, s)\right| \\
&\quad \le \left|W(x, \lambda\mu, s) - W^n(x, \lambda\mu, s)\right| + \lambda\left|W^n(x, \mu, s) - W(x, \mu, s)\right| \\
&\quad \to 0.
\end{aligned}$$

Q.E.D.

LEMMA 9A—Monotonicity: *Let $\widehat{W} \in \mathcal{M}$ and $\widetilde{W} \in \mathcal{M}$ be such that $\widehat{W} \le \widetilde{W}$. Then $(T^*\widehat{W}) \le (T^*\widetilde{W})$.*

PROOF: Given (x, μ, s), let $(\widehat{a}^*, \widehat{\gamma}^*)$ and $(\widetilde{a}^*, \widetilde{\gamma}^*)$ be the solutions to $(T^*\widehat{W})$ and $(T^*\widetilde{W})$, respectively. Then,

$$\begin{aligned}
&\left(T^*\widehat{W}\right)(x, \mu, s) \\
&\quad = \mathrm{SP}\min_{\gamma\ge 0}\max_{a\in A(x,s)}\left\{\mu h_0(x, a, s) + \gamma h_1(x, a, s) + \beta \mathrm{E}\widehat{W}\left(\ell\left(x, a, s'\right), \varphi(\mu, \gamma), s'\right)\right\} \\
&\quad = \mu h_0\left(x, \widehat{a}^*, s\right) + \widehat{\gamma}^* h_1\left(x, \widehat{a}^*, s\right) + \beta \mathrm{E}\widehat{W}\left(\ell\left(x, \widehat{a}^*, s'\right), \varphi\left(\mu, \widehat{\gamma}^*\right), s'\right) \\
&\quad \le \mu h_0\left(x, \widehat{a}^*, s\right) + \widetilde{\gamma}^* h_1\left(x, \widehat{a}^*, s\right) + \beta \mathrm{E}\widehat{W}\left(\ell\left(x, \widehat{a}^*, s'\right), \varphi\left(\mu, \widetilde{\gamma}^*\right), s'\right) \\
&\quad \le \mu h_0\left(x, \widehat{a}^*, s\right) + \widetilde{\gamma}^* h_1\left(x, \widehat{a}^*, s\right) + \beta \mathrm{E}\widetilde{W}\left(\ell\left(x, \widehat{a}^*, s'\right), \varphi\left(\mu, \widetilde{\gamma}^*\right), s'\right) \\
&\quad \le \mu h_0\left(x, \widetilde{a}^*, s\right) + \widetilde{\gamma}^* h_1\left(x, \widetilde{a}^*, s\right) + \beta \mathrm{E}\widetilde{W}\left(\ell\left(x, \widetilde{a}^*, s'\right), \varphi\left(\mu, \widetilde{\gamma}^*\right), s'\right) \\
&\quad = \mathrm{SP}\min_{\gamma\ge 0}\max_{a\in A(x,s)}\left\{\mu h_0(x, a, s) + \gamma h_1(x, a, s) + \beta \mathrm{E}\widetilde{W}\left(\ell\left(x, a, s'\right), \varphi(\mu, \gamma), s'\right)\right\} \\
&\quad = \left(T^*\widetilde{W}\right)(x, \mu, s),
\end{aligned}$$

where the second inequality follows from $\widehat{W} \le \widetilde{W}$, and the first and the third inequalities follow from the minimality of $\widehat{\gamma}^*$ and the maximality of $\widetilde{a}^*$, respectively. *Q.E.D.*

LEMMA 10A—Discounting: *For all $W \in \mathcal{M}$, and $r \in \mathcal{R}_+$, $T^*(W + r) \le T^*W + \beta r$.*

PROOF: First, note that $(W + r)(x, \mu, s) = \mu\omega(x, \mu, s) + r$, therefore $\Psi_{W+r}(x, \mu, s) = \Psi_W(x, \mu, s)$. Let $(a^*, \gamma^*) \in \Psi_W(x, \mu, s)$; then

$$\begin{aligned}
\left(T^*(W + r)\right)(x, \mu, s) &= \mu h_0\left(x, a^*, s\right) + \gamma^* h_1\left(x, a^*, s\right) + \beta\left(\mathrm{E}\left[W\left(x^{*\prime}, \varphi\left(\mu, \gamma^*\right), s'\right)|s\right] + r\right) \\
&= \left(T^*W\right)(x, \mu, s) + \beta r.
\end{aligned}$$

Q.E.D.

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