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EXISTENCE OF COMPETITIVE EQUILIBRIUM IN AN OPTIMAL GROWTH MODEL WITH HETEROGENEOUS AGENTS AND ENDOGENOUS LEISURE

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This paper proves the existence of competitive equilibrium in a single-sector dynamic economy with heterogeneous agents, elastic labor supply, and complete asset markets. The method of proof relies on some recent results concerning the existence of Lagrange multipliers in infinite-dimensional spaces and their representation as a summable sequence and a direct application of the inward-boundary fixed point theorem.

Keywords: Optimal Growth Model, Lagrange Multipliers, Competitive Equilibrium, Elastic Labor Supply

1. INTRODUCTION

Since the seminal work of Ramsey (1928), optimal growth models have played a central role in modern macroeconomics. Classical growth theory relies on the assumption that labor is supplied in fixed amounts, although the original paper of Ramsey did include the disutility of labor as an argument in consumers' utility functions. Subsequent research in applied macroeconomics (theories of business

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cycle fluctuations) has reassessed the role of the labor–leisure choice in the process of growth. Currently, intertemporal models with elastic labor continue to be the standard setting used to model many issues in applied macroeconomics.

Our purpose is to prove the existence of competitive equilibrium for the basic neoclassical model with elastic labor with assumptions less stringent than those in the literature, using some recent results [see Le Van and Saglam (2004)] concerning the existence of Lagrange multipliers in infinite-dimensional spaces and their representation as a summable sequence.

Previous work addressing the existence of competitive equilibrium in intertemporal models attacks the problem of existence from an abstract point of view. Following the early work of Peleg and Yaari (1970), this approach is based on separation arguments applied to arbitrary vector spaces [see Bewley (1972), Bewley (1982), Aliprantis et al. (1990), and Dana and Le Van (1991)]. The advantage of this approach is that it yields general results capable of application in a wide variety of models. However, it requires a high level of abstraction and some strong assumptions.

Le Van and Vailakis (2004), to prove the existence of competitive equilibrium in a model with a representative agent and elastic labor supply, impose relatively strong assumptions.[1] In this paper, the existence of equilibrium cannot be established using marginal utilities because we may have boundary solutions.

Recently, Le Van et al. (2007) extended the canonical representative-agent Ramsey model to include heterogeneous agents and elastic labor supply and used supermodularity to establish the convergence of optimal paths. The novelty in their work is that relatively impatient consumers have their consumption and leisure converging to zero and any Pareto-optimal capital path converges to a limit point as time tends toward infinity. However, if the limit points of the Pareto-optimal capital paths are not bounded away from zero, then their convergence results do not ensure the existence of equilibrium.

To obtain the convergence results, they impose strong assumptions that are not used in our paper.[2] Following the Negishi approach (1960), our strategy for tackling the question of existence relies on exploiting the link between Pareto optima and competitive equilibria. We show that there exist Lagrange multipliers that can be used as a price system, such that together with the Pareto-optimal solution they constitute an equilibrium with transfers. These transfers depend on the individual weights involved in the social welfare function. An equilibrium exists provided that there is a set of welfare weights such that the corresponding transfers equal zero. The model in which we establish existence is with complete contingent commodity Arrow–Debreu markets (as opposed to trading in sequential markets) and the prices and transfers are sufficient for decentralizing the optimal allocation. We also do not require, with additional assumptions, as in Le Van et al. (2007), that the optimal capital stock converges in the long run to a strictly positive value in order to get prices in ℓ^1_+.

The organization of the paper is as follows. In Section 2, we present the model and provide sufficient conditions on the objective function and the constraint functions so that Lagrange multipliers can be presented by an ℓ^1_+ sequence. We characterize some dynamic properties of the Pareto-optimal paths of capital and of consumption–leisure. In particular, we prove that the optimal consumption and leisure paths of the more impatient agents will converge to zero in the long run [see Becker (1980) for a similar result in a sequential trading model] with a very elementary proof compared to the one in Le Van et al. (2007), which uses supermodularity for lattice programming. In Section 3, we prove the existence of competitive equilibrium using the Negishi approach and the inward-boundary fixed point theorem.

2. THE MODEL

We study an intertemporal model with $m \geq 1$ consumers and one firm. There is a single produced good in each period that is either consumed or invested as capital. The preferences of each consumer, $i = 1, \ldots, m$, take the additive form $\sum_{t=0}^{\infty} \beta_i^t u^i(c_t^i, l_t^i)$, where $\beta_i \in (0, 1)$ is the discount factor. At date t, consumer i consumes c_t^i of the good, enjoys a quantity of leisure l_t^i, and supplies a quantity of labor L_t^i, which are normalized so that $l_t^i + L_t^i = 1$. Production possibilities are given by the gross production function F and a physical depreciation $\delta \in (0, 1)$. Denote $F(k_t, \sum_{i=1}^m L_t^i) + (1 - \delta)k_t = f(k_t, \sum_{i=1}^m L_t^i)$.

We next specify a set of restrictions on preferences and the production technology.[3]

(U1) u^i is continuous, concave, and increasing on $\mathbf{R}_+ \times [0, 1]$ and strictly increasing and strictly concave on $\mathbf{R}_{++} \times (0, 1)$.

(U2) $u^i(0, 0) = 0$.

(U3) u^i is twice continuously differentiable on $\mathbf{R}_{++} \times (0, 1)$ with partial derivatives satisfying the Inada conditions: $\lim_{c \to 0} u_c^i(c, l) = +\infty, \forall l \in (0, 1]$ and $\lim_{l \to 0} u_l^i(c, l) = +\infty, \forall c > 0$.

We extend the utility functions on $\mathbf{R}^2$ by imposing $u^i(c, l) = -\infty$ if $(c, l) \in \mathbf{R}^2 \setminus \{\mathbf{R}_+ \times [0, 1]\}$.

The assumptions on the production function $F : \mathbf{R}^2_+ \to \mathbf{R}_+$ are as follows:

(F1) F is continuous, concave, increasing on $\mathbf{R}^2_+$, and strictly increasing on $\mathbf{R}^2_{++}$.

(F2) $F(0, 0) = 0$.

(F3) F is twice continuously differentiable on $\mathbf{R}^2_{++}$ with partial derivatives satisfying the Inada conditions: $\lim_{k \to 0} F_k(k, L) = +\infty, \ \forall L > 0$, $\lim_{k \to +\infty} F_k(k, m) < \delta$ and $\lim_{L \to 0} F_L(k, L) = +\infty, \forall k > 0$.

We extend the function F over $\mathbf{R}^2$ by imposing $F(k, L) = -\infty$ if $(k, L) \notin \mathbf{R}^2_+$.

For any initial condition $k_0 \geq 0$, when a sequence $\mathbf{k} = (k_0, k_1, k_2, \ldots, k_t, \ldots)$ is such that $0 \leq k_{t+1} \leq f(k_t, m)$ for all t, we say it is feasible from k_0 and we denote the class of feasible capital paths by $\Pi(k_0)$. Let $(\mathbf{c}^1, \mathbf{c}^2, \ldots, \mathbf{c}^i, \ldots, \mathbf{c}^m)$, where $\mathbf{c}^i = (c_0^i, c_1^i, \ldots, c_t^i, \ldots)$, denotes the vector of consumption and $(\mathbf{l}^1, \mathbf{l}^2, \ldots, \mathbf{l}^i, \ldots, \mathbf{l}^m)$, where $\mathbf{l}^i = (l_0^i, l_1^i, \ldots, l_t^i, \ldots)$, the vector of leisure of all agents. A pair of consumption–leisure sequences $(\mathbf{c}^i, \mathbf{l}^i) = (c_t^i, l_t^i)_{t=0}^{\infty}$ is feasible from $k_0 \geq 0$ if there exists a sequence $\mathbf{k} \in \Pi(k_0)$ that satisfies $\forall t$,

$$\sum_{i=1}^{m} c_t^i + k_{t+1} \leq f\left(k_t, \sum_{i=1}^{m}(1 - l_t^i)\right) \quad \text{and} \quad 0 \leq l_t^i \leq 1.$$

The set of feasible consumption–leisure sequences from k_0 is denoted by $\sum(k_0)$. Assumption (**F3**) implies that

$$f_k(+\infty, m) = F_k(+\infty, m) + (1 - \delta) < 1,$$
$$f_k(0, m) = F_k(0, m) + (1 - \delta) > 1.$$

It follows that there exists $\overline{k} > 0$ such that (i) $f(\overline{k}, m) = \overline{k}$, (ii) $k > \overline{k}$ implies $f(k, m) < k$, and (iii) $k < \overline{k}$ implies $f(k, m) > k$. Therefore for any $\mathbf{k} \in \Pi(k_0)$, we have $0 \leq k_t \leq \max(k_0, \overline{k})$. Thus, a feasible sequence $\mathbf{k}$ is in ℓ_+^{∞}, which in turn implies that any feasible sequence $(\mathbf{c}, \mathbf{l})$ belongs to $\ell_+^{\infty} \times [0, 1]^{\infty}$.

In what follows, we study the Pareto optimum problem. We show that the Lagrange multipliers are in ℓ_+^1. Then these multipliers will be used to define a price and wage system for the equilibrium.

Let $\Delta = \{\eta_1, \eta_2, \ldots, \eta_m | \eta_i \geq 0 \text{ and } \sum_{i=1}^{m} \eta_i = 1\}$. Given a vector of welfare weights $\eta \in \Delta$, define the Pareto problem

$$\max \sum_{i=1}^{m} \eta_i \sum_{t=0}^{\infty} \beta_i^t u^i(c_t^i, l_t^i), \qquad (\mathbf{Q})$$

$$\text{s.t.} \sum_{i=1}^{m} c_t^i + k_{t+1} \leq f\left(k_t, \sum_{i=1}^{m}(1 - l_t^i)\right), \quad \forall t,$$
$$\forall t,\ \forall i,\ c_t^i \geq 0,\ l_t^i \geq 0,\ l_t^i \leq 1,\ k_t \geq 0,\ \text{and } k_0 \text{ given.}$$

Note that, for all $k_0 \geq 0$, $0 \leq k_t \leq \max(k_0, \overline{k})$; thus $0 \leq c_t^i \leq f(\max(k_0, \overline{k}), m) \equiv A$, $\forall t$, $\forall i = 1, \ldots, m$. Therefore, the sequence $(u^i)_n = \sum_{i=1}^{n} \beta_i^t u^i(c_t^i, l_t^i)$ is increasing and bounded and will converge. Thus, we can write

$$\sum_{i=1}^{m} \eta_i \sum_{t=0}^{\infty} \beta_i^t u^i\left(c_t^i, l_t^i\right) = \sum_{t=0}^{\infty} \sum_{i=1}^{m} \eta_i \beta_i^t u^i\left(c_t^i, l_t^i\right).$$

Let $\mathbf{x} = (\mathbf{c}, \mathbf{k}, \mathbf{l}) \in (\ell_+^{\infty})^m \times \ell_+^{\infty} \times (\ell_+^{\infty})^m$.

Define

$$\mathcal{F}(\mathbf{x}) = -\sum_{t=0}^{\infty}\sum_{i=1}^{m} \eta_i \beta_i^t u^i\left(c_t^i, l_t^i\right),$$

$$\Phi_t^1(\mathbf{x}) = \sum_{i=1}^{m} c_t^i + k_{t+1} - f\left(k_t, \sum_{i=1}^{m}(1-l_t^i)\right),$$

$$\Phi_t^{2i}(\mathbf{x}) = -c_t^i, \quad \Phi_t^3(\mathbf{x}) = -k_t, \quad \Phi_t^{4i}(\mathbf{x}) = -l_t^i, \quad \Phi_t^{5i}(\mathbf{x}) = l_t^i - 1,$$

$$\Phi_t = \left(\Phi_t^1, \Phi_t^{2i}, \Phi_{t+1}^3, \Phi_t^{4i}, \Phi_t^{5i}\right), \ \forall t, \forall i = 1, \ldots, m.$$

The Pareto problem can be written as

$$\min\ \mathcal{F}(\mathbf{x}) \qquad \textbf{(P)}$$

$$\text{s.t.}\ \ \Phi(\mathbf{x}) \le \mathbf{0},\ \ \mathbf{x} \in (\ell_+^\infty)^m \times \ell_+^\infty \times (\ell_+^\infty)^m,$$

where

$$\mathcal{F}\ :\ (\ell_+^\infty)^m \times \ell_+^\infty \times (\ell_+^\infty)^m \to \mathbf{R} \cup \{+\infty\},$$

$$\Phi = (\Phi_t)_{t=0,\ldots,\infty} : (\ell_+^\infty)^m \times \ell_+^\infty \times (\ell_+^\infty)^m \to \mathbf{R} \cup \{+\infty\}.$$

Let

$$C = \text{dom}(\mathcal{F}) = \{\mathbf{x} \in (\ell_+^\infty)^m \times \ell_+^\infty \times (\ell_+^\infty)^m | \mathcal{F}(\mathbf{x}) < +\infty\},$$

$$\Gamma = \text{dom}(\Phi) = \{\mathbf{x} \in (\ell_+^\infty)^m \times l_+^\infty \times (\ell_+^\infty)^m | \Phi_t(\mathbf{x}) < +\infty,\ \forall t\}.$$

The following theorem follows from Theorem 1 and Theorem 2 in Le Van and Saglam (2004) [see also Dechert (1982)].

THEOREM 1. *Let* $\mathbf{x}, \mathbf{y} \in (\ell_+^\infty)^m \times \ell_+^\infty \times (\ell_+^\infty)^m$, $T \in N$. *Define*

$$x_t^T(\mathbf{x}, \mathbf{y}) = \begin{cases} x_t & if\ \ t \le T \\ y_t & if\ \ t > T. \end{cases}$$

Suppose that two following assumptions are satisfied:
(T1) If $\mathbf{x} \in C$, $\mathbf{y} \in (\ell_+^\infty)^m \times \ell_+^\infty \times (\ell_+^\infty)^m$ *and* $\forall T \ge T_0$, $\mathbf{x}^T(\mathbf{x}, \mathbf{y}) \in C$, *then* $\mathcal{F}(\mathbf{x}^T(\mathbf{x}, \mathbf{y})) \to \mathcal{F}(\mathbf{x})$ *when* $T \to \infty$.
(T2) If $\mathbf{x} \in \Gamma$, $\mathbf{y} \in \Gamma$ *and* $\mathbf{x}^T(\mathbf{x}, \mathbf{y}) \in \Gamma$, $\forall T \ge T_0$, *then*

$$(a)\ \Phi_t(\mathbf{x}^T(\mathbf{x}, \mathbf{y})) \to \Phi_t(\mathbf{x})\, as\ T \to \infty.$$

$$(b)\ \exists M\ \ s.t.\ \forall T \ge T_0,\ \|\Phi_t(\mathbf{x}^T(\mathbf{x}, \mathbf{y}))\| \le M.$$

$$(c)\ \forall N \ge T_0,\ \lim_{t\to\infty}[\Phi_t(\mathbf{x}^T(\mathbf{x}, \mathbf{y})) - \Phi_t(\mathbf{y})] = 0.$$

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Let $\mathbf{x}^*$ *be a solution to* (***P***) *and let* $\bar{\mathbf{x}} \in C$ *satisfy the strong Slater condition:*

$$\sup_t \Phi_t(\bar{\mathbf{x}}) < 0.$$

Suppose $\mathbf{x}^T(\mathbf{x}^*, \bar{\mathbf{x}}) \in C \cap \Gamma$. *Then there exist* $\Lambda \in l^1_+ \backslash \{0\}$ *such that*

$$\mathcal{F}(\mathbf{x}) + \Lambda\Phi(\mathbf{x}) \geq \mathcal{F}(\mathbf{x}^*) + \Lambda\Phi(\mathbf{x}^*),\ \forall \mathbf{x} \in (\ell^\infty)^m \times \ell^\infty \times (\ell^\infty)^m$$

and $\Lambda\Phi(\mathbf{x}^*) = 0$.

Obviously, for any $\eta \in \Delta$, an optimal path will depend on η. In what follows, if possible, we will suppress η and denote by $(\mathbf{c}^{*i}, \mathbf{k}^*, \mathbf{L}^{*i}, \mathbf{l}^{*i})$ any optimal path for each agent i. The following proposition characterizes the Lagrange multipliers of the Pareto problem. Let $I = \{i \mid \eta_i > 0\}$

PROPOSITION 1. *If* $\mathbf{x}^* = (\mathbf{c}^{*i}, \mathbf{k}^*, \mathbf{l}^{*i})$ *is a solution to the Pareto problem* (**Q**) *then there exist* $\forall i = 1, \ldots, m$, $\lambda = (\lambda^1, \lambda^{2i}, \lambda^3, \lambda^{4i}, \lambda^{5i}) \in \ell^1_+ \times (\ell^1_+)^m \times \ell^1_+ \times (\ell^1_+)^m \times (\ell^1_+)^m$, $\lambda \neq \mathbf{0}$, *such that, for any* $((\mathbf{c}^i, \mathbf{l}^i), \mathbf{k}, \mathbf{L})$,

$$\begin{aligned}&\sum_{t=0}^{\infty}\sum_{i=1}^{m}\eta_i\beta_i^t u^i(c_t^{*i}, l_t^{*i}) - \sum_{t=0}^{\infty}\lambda_t^1\left(\sum_{i=1}^{m}c_t^{*i} + k_{t+1}^* - f(k_t^*, L_t^*)\right) \\ &\quad + \sum_{t=0}^{\infty}\sum_{i=1}^{m}\lambda_t^{2i}c_t^{*i} + \sum_{t=0}^{\infty}\lambda_t^3 k_t^* + \sum_{t=0}^{\infty}\sum_{i=1}^{m}\lambda_t^{4i}l_t^{*i} + \sum_{t=0}^{\infty}\sum_{i=1}^{m}\lambda_t^{5i}(1 - l_t^{*i}) \\ &\geq \sum_{t=0}^{\infty}\sum_{i=1}^{m}\eta_i\beta_i^t u^i(c_t^i, l_t^i) - \sum_{t=0}^{\infty}\lambda_t^1\left(\sum_{i=1}^{m}c_t^i + k_{t+1} - f(k_t, L_t)\right) \\ &\quad + \sum_{t=0}^{\infty}\sum_{i=1}^{m}\lambda_t^{2i}c_t^i + \sum_{t=0}^{\infty}\lambda_t^3 k_t + \sum_{t=0}^{\infty}\sum_{i=1}^{m}\lambda_t^{4i}l_t^i + \sum_{t=0}^{\infty}\sum_{i=1}^{m}\lambda_t^{5i}(1 - l_t^i),\end{aligned} \tag{1}$$

$$\lambda_t^1\left[\sum_{i=1}^{m}c_t^{*i} + k_{t+1}^* - f\left(k_t^*, \sum_{i=1}^{m}L_t^{*i}\right)\right] = 0, \tag{2}$$

$$\lambda_t^{2i}c_t^{*i} = 0, \forall i = 1, \ldots, m, \tag{3}$$

$$\lambda_t^3 k_t^* = 0, \tag{4}$$

$$\lambda_t^{4i}l_t^{*i} = 0, \forall i = 1, \ldots, m, \tag{5}$$

$$\lambda_t^{5i}(1 - l_t^{*i}) = 0, \forall i = 1, \ldots, m, \tag{6}$$

$$0 \in \eta_i\beta_i^t\partial_1 u^i(c_t^{*i}, l_t^{*i}) - \{\lambda_t^1\} + \{\lambda_t^{2i}\}, \forall i \in I, \tag{7}$$

$$0 \in \eta_i\beta_i^t\partial_2 u^i(c_t^{*i}, l_t^{*i}) - \lambda_t^1\partial_2 f(k_t^*, L_t^*) + \{\lambda_t^{4i}\} - \{\lambda_t^{5i}\}, \forall i \in I, \tag{8}$$

$$0 \in \lambda_t^1\partial_1 f(k_t^*, L_t^*) + \{\lambda_t^3\} - \{\lambda_{t-1}^1\}, \tag{9}$$

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where $L_t^* = \sum_{i=1}^m L_t^{*i} = \sum_{i=1}^m (1 - l_t^{*i})$ *and* $\partial_j u(c_t^{*i}, l_t^{*i})$ *and* $\partial_j f(k_t^*, L_t^*)$ *respectively denote the projection on the* j*th component of the subdifferential of function* u *at* (c_t^{*i}, l_t^{*i}) *and the function* f *at* (k_t^*, L_t^*). [4]

Proof. We show that the strong Slater condition holds. Because $f_k(0, m) > 1$,[5] for all $k_0 > 0$, there exists some $\widehat{k} \in (0, k_0)$ such that $0 < \widehat{k} < f(\widehat{k}, m)$ and $0 < \widehat{k} < f(k_0, m)$. Thus, there exist two small positive numbers $\varepsilon, \varepsilon_1$ such that

$$0 < \widehat{k} + \varepsilon < f(\widehat{k}, m - \varepsilon_1) \text{ and } 0 < \widehat{k} + \varepsilon < f(k_0, m - \varepsilon_1).$$

Denote $\bar{\mathbf{x}} = (\bar{\mathbf{c}}, \bar{\mathbf{k}}, \bar{\mathbf{l}})$, where $\bar{\mathbf{c}} = (\bar{\mathbf{c}}^i)_{i=1}^m$, $\bar{\mathbf{l}} = (\bar{\mathbf{l}}^i)_{i=1}^m$, $\bar{\mathbf{k}} = (k_0, \widehat{k}, \widehat{k}, \ldots)$, and

$$\bar{\mathbf{c}}^i = (\bar{c}_t^i)_{t=0,\ldots,\infty} = \left(\frac{\varepsilon}{m}, \frac{\varepsilon}{m}, , \ldots\right), \; \bar{\mathbf{l}}^i = (\bar{l}_t^i)_{t=0,\ldots,\infty} = \left(\frac{\varepsilon_1}{m}, \frac{\varepsilon_1}{m}, \ldots\right).$$

We have

$$\Phi_0^1(\bar{\mathbf{x}}) = \sum_{i=0}^m c_0^i + k_1 - f\left(k_0, \sum_{i=1}^m (1 - l_0^i)\right) = \varepsilon + \widehat{k} - f(k_0, m - \varepsilon_1) < 0,$$

$$\Phi_1^1(\bar{\mathbf{x}}) = \sum_{i=0}^m c_1^i + k_2 - f\left(k_1, \sum_{i=1}^m (1 - l_1^i)\right) = \varepsilon + \widehat{k} - f(\widehat{k}, m - \varepsilon_1) < 0,$$

$$\Phi_t^1(\bar{\mathbf{x}}) = \varepsilon + \widehat{k} - f(\widehat{k}, m - \varepsilon_1) < 0, \; \forall t \geq 2,$$
$$\Phi_t^{2i}(\bar{\mathbf{x}}) = -\bar{c}_t^i = -\frac{\varepsilon}{m} < 0, \; \forall t \geq 0, \forall i = 1, \ldots, m,$$

$$\Phi_0^3(\bar{\mathbf{x}}) = -k_0 < 0, \; \Phi_t^3(\bar{\mathbf{x}}) = -\widehat{k} < 0 \;\; \forall t \geq 1,$$

$$\Phi_t^{4i}(\bar{\mathbf{x}}) = -\frac{\varepsilon_1}{m} < 0, \; \forall t \geq 0, \forall i = 1, \ldots, m,$$
$$\Phi_t^{5i}(\bar{\mathbf{x}}) = \frac{\varepsilon_1}{m} - 1 < 0, \forall t \geq 0, \forall i = 1, \ldots, m.$$

Therefore, the strong Slater condition is satisfied.

It is obvious that, $\forall T$, $\mathbf{x}^T(\mathbf{x}^*, \bar{\mathbf{x}})$ belongs to $(\ell_+^\infty)^m \times l_+^\infty \times (\ell_+^\infty)^m$.

As in Le Van and Saglam (2004), Assumption (**T2**) is satisfied. We now check Assumption (**T1**).

For any $\widetilde{\mathbf{x}} \in C$, $\widetilde{\widetilde{\mathbf{x}}} \in (\ell_+^\infty)^m \times \ell_+^\infty \times (\ell_+^\infty)^m$ such that for any T, $\mathbf{x}^T(\widetilde{\mathbf{x}}, \widetilde{\widetilde{\mathbf{x}}}) \in C$, we have

$$\mathcal{F}(\mathbf{x}^T(\widetilde{\mathbf{x}}, \widetilde{\widetilde{\mathbf{x}}})) = -\sum_{t=0}^T \sum_{i=1}^m \eta_i \beta_i^t u^i\left(\widetilde{c}_t^i, \widetilde{l}_t^i\right) - \sum_{t=T+1}^\infty \sum_{i=1}^m \eta_i \beta_i^t u^i\left(\widetilde{\widetilde{c}}_t^i, \widetilde{\widetilde{l}}_t^i\right).$$

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As $\widetilde{\widetilde{\mathbf{x}}} \in (\ell_+^\infty)^m \times \ell_+^\infty \times (\ell_+^\infty)^m$, $\sup_t |\widetilde{\widetilde{c}}_t| < +\infty$, there exists $A > 0, \forall t$ such that $|\widetilde{\widetilde{c}}_t| \leq A$. Because $\beta_i \in (0, 1)$ as $T \to \infty$, we have

$$0 \leq \sum_{t=T+1}^{\infty} \sum_{i=1}^{m} \eta_i \beta_i^t u^i \left(\widetilde{\widetilde{c}}_t^i, \widetilde{\widetilde{l}}_t^i\right) \leq u(A, 1) \sum_{t=T+1}^{\infty} \sum_{i=1}^{m} \eta_i \beta_i^t = u(A, 1) \sum_{i=1}^{m} \sum_{t=T+1}^{\infty} \eta_i \beta_i^t \to 0,$$

where $u(A, 1) = \max\{u_i(A, 1), i = 1, \ldots, m\}$. Hence $\mathcal{F}(\mathbf{x}^T(\widetilde{\mathbf{x}}, \widetilde{\widetilde{\mathbf{x}}})) \to \mathcal{F}(\widetilde{\mathbf{x}})$ when $T \to \infty$. Taking account of the Theorem 1, we get (1)–(6).

Obviously, $\cap_{i=1}^m \mathrm{ri}(\mathrm{dom}(u^i)) \neq \emptyset$ where $\mathrm{ri}(\mathrm{dom}(u^i))$ is the relative interior of $\mathrm{dom}(u^i)$. It follows from the Proposition 6.5.5 in Florenzano and Le Van (2001) that we have

$$\partial \sum_{i=1}^{m} \eta_i \beta_i^t u^i \left(c_t^{*i}, l_t^{*i}\right) = \eta_i \beta_i^t \sum_{i=1}^{m} \partial u^i \left(c_t^{*i}, l_t^{*i}\right).$$

We then get (7)–(9) as the Kuhn–Tucker first-order conditions. ■

Remark 1.

(1) It is easy to prove that $\eta_i = 0 \Rightarrow c_t^{*i} = 0,\ l_t^{*i} = 0,\ \forall t$.
(2) For any optimal solution $(\mathbf{c}^{*i}, \mathbf{k}^*, \mathbf{l}^{*i})$, we have for any t, any $i \in I$, $\partial_1 u^i(c_t^{*i}, l_t^{*i}) \neq \emptyset$, $\partial_2 u^i(c_t^{*i}, l_t^{*i}) \neq \emptyset$, $\partial_1 f(k_t^*, L_t^*) \neq \emptyset$, $\partial_2 f(k_t^*, L_t^*) \neq \emptyset$, where $L_t^* = m - \sum_i l_t^{*i}$.
(3) For $i \in I$, we have $c_t^{*i} > 0$ iff $l_t^{*i} > 0$. In this case, $\partial_1 u^i(c_t^{*i}, l_t^{*i}) = \{u_c^i(c_t^{*i}, l_t^{*i})\}$, $\partial_2 u^i(c_t^{*i}, l_t^{*i}) = \{u_l^i(c_t^{*i}, l_t^{*i})\}$.
(4) For any $k_0 > 0$, there exists t with $\sum_i c_t^{*i} > 0$ and hence $\sum_i l_t^{*i} > 0$ (if not, the value of the Pareto problem is null which is a contradiction).

In the following proposition, we will prove the positiveness of the optimal capital path.

PROPOSITION 2. *If $k_0 > 0$, the optimal capital path satisfies $k_t^* > 0, \forall t$.*

Proof. Let $k_0 > 0$ but assume that $k_1^* = 0$. From (9), $L_1^* = 0$. This implies that $\sum_i c_1^{*i} = 0$ and $l_1^{*i} = 1, \forall i$: a contradiction with (7). Hence $k_1^* > 0$. By induction, $k_t^* > 0, \forall t > 0$. ■

Remark 2. From (9) and Proposition 2, if $k_0 > 0$, we have $L_t^* > 0$ for any $t \geq 0$. Hence, for any $t \geq 0$, $\partial_1 f(k_t^*, L_t^*) = \{f_k(k_t^*, L_t^*)\}$, $\partial_2 f(k_t^*, L_t^*) = \{f_L(k_t^*, L_t^*)\}$.

PROPOSITION 3. *Let $k_0 > 0$.*

(a) *With any $\eta \in \Delta$, there exists a unique solution, $\{(\mathbf{c}^{*i}), (\mathbf{l}^{*i}), \mathbf{k}^*\}$, to the Pareto problem. We have the following: For any $t \geq 0$,*

$$\lambda_t^1(\eta) \in \cap_{i \in I}\ \eta_i \beta_i^t \partial_1 u^i \left(c_t^{*i}, l_t^{*i}\right), \tag{10}$$

$$\lambda_t^1(\eta) f_L(k_t^*, L_t^*) \in \cap_{i \in I}\ \eta_i \beta_i^t \partial_2 u^i \left(c_t^{*i}, l_t^{*i}\right), \tag{11}$$

and for any $t \geq 1$,

$$0 \in \lambda_t^1(\eta) \partial_1 f(k_t^*, L_t^*) - \lambda_{t-1}^1(\eta). \tag{12}$$

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(b) *Conversely, if the sequences* $\mathbf{c}^{*i}, \mathbf{l}^{*i}, \mathbf{k}^*, \mathbf{L}^*$ *satisfy*

$$L_t^* = \sum_i (1 - l_t^{*i}),\ \forall t \geq 0,$$
$$\sum_i c_t^{*i} = f(k_t^*, L_t^*) - k_{t+1}^*,\ \forall t \geq 0,$$
$$k_0^* = k_0$$

and if there exists $\lambda^1 \in \ell_+^1$ *that satisfies (10), (11), and (12), then* $\mathbf{c}^{*i}, \mathbf{l}^{*i}, \mathbf{k}^*$ *solve the Pareto problem with weights* η *and* λ^1 *is an associated multiplier.*

Proof. This is easy. ■

PROPOSITION 4. *Let* $k_0 > 0$. *Then there exists a unique multiplier* $\lambda^{\mathbf{1}} \in \ell^1$.

Proof. Existence has been proven. Let us prove uniqueness. First observe that, from Remark 2, we have $\partial_1 f(k_t^*, L_t^*) = \{f_k(k_t^*, L_t^*)\}$, $\partial_2 f(k_t^*, L_t^*) = \{f_L(k_t^*, L_t^*)\}$, for every t. First, because $k_0 > 0$, there exists t with $\sum_i c_t^{*i} > 0$. We then have three cases.

(a) If for any t, $\sum_i c_t^{*i} > 0$, then $\lambda_t^1(\eta) = \eta_j \beta_j^t u^j(c_t^{*j}, l_t^{*j})$ with $c_t^{*j} > 0$.
(b) When $\sum_i c_0^{*i} > 0$, let T be the first date where $\sum_i c_T^{*i} = 0$ (and hence $\sum_i l_T^{*i} = 0$). From $t = 0$ to $t = T - 1$, $\lambda_t^1(\eta)$ is uniquely determined. We have, from (12), $\lambda_T^1(\eta) f_k(k_T^*, m) = \lambda_{T-1}^1(\eta)$ and $\lambda_T^1(\eta)$ is uniquely determined. But we also have $\lambda_{T+1}^1(\eta) f_k(k_{T+1}^*, L_{T+1}^*) = \lambda_T^1(\eta)$ and $\lambda_{T+1}^1(\eta)$ is uniquely determined. By induction, the result holds for every t.
(c) When $\sum_i c_0^{*i} = 0$, let T be the first date where $\sum_i c_T^{*i} > 0$. In this case, $\lambda_T^1(\eta) = \eta_j \beta_j^t u_c^j(c_T^{*j}, l_T^{*j})$ with $c_T^{*j} > 0$. We have, from (12), $\lambda_T^1(\eta) f_k(k_T^*, L_T^*) = \lambda_{T-1}^1(\eta)$ and $\lambda_{T-1}^1(\eta)$ is uniquely determined. By backward induction, $\lambda_t^1(\eta)$ is uniquely determined from 0 to $T - 1$. We also have $\lambda_{T+1}^1(\eta) f_k(k_{T+1}^*, L_{T+1}^*) = \lambda_T^1(\eta)$ and $\lambda_{T+1}^1(\eta)$ is uniquely determined. By forward induction, the result holds for every $t \geq T + 1$. ■

Let us recall that $I = \{i \mid \eta_i > 0\}$. Denote $\beta = \max\{\beta_i | i \in I\}$, $I_1 = \{i \in I \mid \beta_i = \beta\}$ and $I_2 = \{i \in I \mid \beta_i < \beta\}$.

We now show that the consumption and leisure paths of all agents with a discount factor less than the maximum one converge to zero. The proof is very simple compared to the one in Le Van et al. (2007), which uses the supermodular structure inspired by lattice programming.

PROPOSITION 5. *If* $(\mathbf{k}^*, \mathbf{c}^{*i}, \mathbf{l}^{*i})$ *denotes the optimal path starting from* k_0, *then* $\forall i \in I_2$, $c_t^{*i} \longrightarrow 0$ *and* $l_t^{*i} \longrightarrow 0$.

Proof. Consider the following problem:

$$V_t(k_t, k_{t+1}) = \max \sum_{i=1}^m \eta_i \beta_i^t u^i\left(c_t^i, l_t^i\right),$$

$$\text{s.t.} \sum_{i=1}^m c_t^i + k_{t+1} \leq F\left(k_t, \sum_{i=1}^m \left(1 - l_t^i\right)\right) + (1 - \delta)k_t.$$

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It is easy to see that the Pareto problem is equivalent to

$$\max \sum_{t=0}^{\infty} V_t(k_t, k_{t+1})$$
$$\text{s.t. } 0 \le k_{t+1} \le F(k_t, m) + (1-\delta)k_t, \ \forall t \ge 0, k_0 \text{ is given.}$$

Observe that

$$V_t(k_t, k_{t+1}) = \beta^t \max \sum_{i=1}^{m} \eta_i \left(\frac{\beta_i}{\beta}\right)^t u^i\left(c_t^i, l_t^i\right),$$
$$\text{s.t. } \sum_{i=1}^{m} c_t^i + k_{t+1} \le F\left(k_t, \sum_{i=1}^{m}\left(1 - l_t^i\right)\right) + (1-\delta)k_t.$$

Denote $Z^t = [\eta_i(\beta_i/\beta)^t]$. From the Berge Maximum Theorem (1959) and the strict concavity and the increasingness of the utility functions, the optimal c^{*i}, l^{*i} are continuous with respect to (Z^t, k_t, k_{t+1}). Denote these functions by $[\Gamma^i(Z^t, k_t^*, k_{t+1}^*), \Lambda^i(Z^t, k_t^*, k_{t+1}^*)]_i$. Let κ^*, ξ^* denote the limit points of k_t^*, k_{t+1}^* when $t \to +\infty$. Then, for $i \in I_2$, $\Gamma^i(Z^t, k_t^*, k_{t+1}^*)$ converges to $\Gamma^i(0_{I_2}, (\eta_i)_{i\in I_2}, \kappa^*, \xi^*) = 0$, and $\Lambda^i(Z^t, k_t^*, k_{t+1}^*)$ converges to $\Lambda^i(0_{I_2}, (\eta_i)_{i\in I_2}, \kappa^*, \xi^*) = 0$. ■

3. EXISTENCE OF COMPETITIVE EQUILIBRIUM

We now give the characterization of competitive equilibrium. Let $\alpha^i > 0$ denote the share of the profit of the firm that is owned by consumer i. We have $\sum_{i=1}^m \alpha^i = 1$. Let $\vartheta^i > 0$ be the share of the initial endowment that is owned by consumer i. Clearly, $\sum_{i=1}^m \vartheta^i = 1$, and $\vartheta^i k_0$ is the endowment of consumer i.

DEFINITION 1. *Let $k_0 > 0$. A competitive equilibrium for this model consists of a sequence of prices $\mathbf{p}^* = (p_t^*)_{t=0}^{\infty}$ for the consumption good, a wage sequence $\mathbf{w}^* = (w_t^*)_{t=0}^{\infty}$ for labor, a price r for the initial capital stock k_0, and an allocation $\{\mathbf{c}^{*i}, \mathbf{k}^*, \mathbf{l}^{*i}, \mathbf{L}^{*i}\}$ such that*

(i)

$$\mathbf{c}^* \in \ell_+^\infty, \mathbf{l}^{*i} \in \ell_+^\infty, \mathbf{L}^{*i} \in \ell_+^\infty, \mathbf{k}^* \in \ell_+^\infty,$$
$$\mathbf{p}^* \in \ell_+^1 \backslash \{0\}, \mathbf{w}^* \in \ell_+^1 \backslash \{0\}, r > 0.$$

(ii) *For every i, $(\mathbf{c}^{*i}, \mathbf{l}^{*i})$ is a solution to the problem*

$$\max \sum_{t=0}^{\infty} \beta_i^t u^i\left(c_t^i, l_t^i\right),$$
$$\text{s.t.} \quad \sum_{t=0}^{\infty} p_t^* c_t^i + \sum_{t=0}^{\infty} w_t^* l_t^i \le \sum_{t=0}^{\infty} w_t^* + \vartheta^i r k_0 + \alpha^i \pi^*,$$

where π^* is the maximum profit of the single firm.

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(iii) *($\mathbf{k}^*, \mathbf{L}^*$) is a solution to the firm's problem*

$$\pi^* = \max \sum_{t=0}^{\infty} p_t^*[f(k_t, L_t) - k_{t+1}] - \sum_{t=0}^{\infty} w_t^* L_t - rk_0,$$

$$\text{s.t.} \quad 0 \leq k_{t+1} \leq f(k_t, L_t), 0 \leq L_t, \forall t.$$

(iv) *Markets clear:* $\forall t$,

$$\sum_{t=1}^{m} c_t^{*i} + k_{t+1}^* = f\left(k_t^*, \sum_{i=1}^{m} L_t^{*i}\right),$$

$$l_t^{*i} + L_t^{*i} = 1, L_t^* = \sum_{i=1}^{m} L_t^{i^*} \textit{and } k_0^* = k_0.$$

We have proved that there exist Lagrange multipliers

$$\lambda(\eta) = [\lambda^{\mathbf{1}}(\eta), \lambda^{\mathbf{2i}}(\eta), \lambda^{\mathbf{3}}(\eta), \lambda^{\mathbf{4i}}(\eta), \lambda^{\mathbf{5i}}(\eta)]$$
$$\in \ell_+^1 \times (\ell_+^1)^m \times \ell_+^1 \times (\ell_+^1)^m \times (\ell_+^1)^m, i = 1, \ldots, m,$$

for the Pareto problem. In what follow, we will prove that, with given ($\mathbf{c}^*$, $\mathbf{k}^*, \mathbf{l}^*, \mathbf{L}^*$), one can associate a sequence of prices, $(p_t^*)_{t=0}^{\infty}$, and a sequence of wages, $(w_t^*)_{t=0}^{\infty}$, defined as

$$p_t^* = \lambda_t^1, \ \forall t,$$
$$w_t^* = \lambda_t^1 f_L(k_t^*, L_t^*), \ \forall t,$$

where $f_L(k_t^*, L_t^*) \in \partial_2 f(k_t^*, L_t^*)$, and a price $r > 0$ for the initial capital stock k_0 such that $(\mathbf{c}^*, \mathbf{k}^*, \mathbf{l}^*, \mathbf{L}^*, \mathbf{p}^*, \mathbf{w}^*, r)$ is a *price equilibrium with transfers* (see Definition 2). The appropriate transfer to each consumer is the amount that just allows the consumer to afford the consumption stream allocated by the social optimization problem. Thus, for a given weight $\eta \in \Delta$, the required transfers are

$$\phi_i(\eta) = \sum_{t=0}^{\infty} p_t^*(\eta) c_t^{i*}(\eta) + \sum_{t=0}^{\infty} w_t^*(\eta) l_t^{i*}(\eta) - \sum_{t=0}^{\infty} w_t^*(\eta) - \vartheta^i r k_0 - \alpha^i \pi^*(\eta),$$

where

$$\pi^*(\eta) = \sum_{t=0}^{\infty} p_t^*(\eta)[f(k_t^*(\eta), L_t^*(\eta)) - k_{t+1}^*(\eta)] - \sum_{t=0}^{\infty} w_t^*(\eta) L_t^*(\eta) - rk_0.$$

According to the Negishi approach, a competitive equilibrium for this economy corresponds to a set of welfare weights $\eta \in \Delta$ such that these transfers are equal to $zero$. Now we define an equilibrium with transfers.

DEFINITION 2. *A given allocation* $\{\mathbf{c}^{*i}, \mathbf{k}^*, \mathbf{l}^{*i}, \mathbf{L}^{*i}\}$, *together with a price sequence* $\mathbf{p}^*$ *for the consumption good, a wage sequence* $\mathbf{w}^*$ *for labor, and a price* r *for the initial capital stock* k_0, *constitute an equilibrium with transfers if*

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(i)

$$\mathbf{c}^* \in (\ell_+^\infty)^m, \mathbf{l}^* \in (\ell_+^\infty)^m, \mathbf{L}^* \in (\ell_+^\infty)^m, \mathbf{k}^* \in \ell_+^\infty,$$
$$\mathbf{p}^* \in \ell_+^1 \backslash \{0\}, \mathbf{w}^* \in \ell_+^1 \backslash \{0\},\ r > 0.$$

(ii) *For every* $i = 1, \ldots, m$, $(\mathbf{c}^{*i}, \mathbf{l}^{*i})$ *is a solution to the problem*

$$\max \sum_{t=0}^{\infty} \beta_i^t u^i \left(c_t^i, l_t^i\right),$$
$$\text{s.t.} \quad \sum_{t=0}^{\infty} p_t^* c_t^i + \sum_{t=0}^{\infty} w_t^* l_t^i \leq \sum_{t=0}^{\infty} p_t^* c_t^{*i} + \sum_{t=0}^{\infty} w_t^* l_t^{*i}.$$

(iii) $(\mathbf{k}^*, \mathbf{L}^*)$ *is a solution to the firm's problem*

$$\pi^* = \max \sum_{t=0}^{\infty} p_t^* [f(k_t, L_t) - k_{t+1}] - \sum_{t=0}^{\infty} w_t^* L_t - r k_0,$$
$$\text{s.t.} \quad 0 \leq k_{t+1} \leq f(k_t, L_t), 0 \leq L_t, \forall t.$$

(iv) *Markets clear:*

$$\sum_{i=1}^{m} c_t^{*i} + k_{t+1}^* = f\left(k_t^*, \sum_{i=1}^{m} L_t^{*i}\right), \quad \forall t,$$
$$L_t^* = \sum_{i=1}^{m} L_t^{*i}, l_t^{*i} = 1 - L_t^{*i} \textit{ and } k_0^* = k_0.$$

The difference between the definition 5—competitive equilibrium and price equilibrium with transfers—is the budget constraints of consumers. If the transfers $\phi_i(\eta) = 0$ for all i, a price equilibrium with transfers is a competitive equilibrium.

Before proving the existence of an equilibrium, we will first prove that any *solution to the Pareto problem*, $\mathbf{x}^* = (\mathbf{c}^{*i}, \mathbf{k}^*, \mathbf{l}^{*i})$, associated with $k_0 > 0$ and $\eta \in \Delta$ is an equilibrium with transfers, with some appropriate prices $(p_t^*) \in \ell_+^1 \backslash \{0\}$ and wages $(w_t^*) \in \ell_+^1 \setminus \{0\}$.

The following result is required.

PROPOSITION 6. *Let* $k_0 > 0$.

(1) *For any* $\varepsilon > 0$*, there exists* T *such that, for any* $\eta \in \Delta$*,*

$$\sum_{T}^{+\infty} \lambda^1{}_t(\eta) \sum_i c_t^{*i} \leq \varepsilon,$$
$$\sum_{T}^{+\infty} \lambda^1{}_t(\eta) f_L(k_t^*, L_t^*) \sum_i l_t^{*i} \leq \varepsilon,$$
$$\sum_{T}^{+\infty} \lambda^1{}_t(\eta) f_L(k_t^*, L_t^*) \leq \varepsilon.$$

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2 *There exists M such that, for any $\eta \in \Delta$,*

$$\sum_{t=0}^{+\infty} \lambda_t^1(\eta) \sum_i c_t^{*i} \leq M,$$

$$\sum_{t=0}^{+\infty} \lambda_t^1(\eta) f_L(k_t^*, L_t^*) \sum_i l_t^{*i} \leq M,$$

$$\sum_{t=0}^{+\infty} \lambda_t^1(\eta) f_L(k_t^*, L_t^*) \leq M.$$

Proof.

(1) We know that there exists A such that $c_t^{*i}(\eta) \leq A,\ \forall t,\ \forall i,\ \forall \eta \in \Delta$. Therefore

$$\frac{\beta^T}{1-\beta} \sum_i u^i(A, 1) \geq \sum_T^{+\infty} \sum_i \eta_i \beta_i^t [u^i(c_t^{*i}, l_t^{*i}) - u^i(0,0)]$$

$$\geq \sum_T^{+\infty} \lambda_t^1 \sum_i c_t^{*i} + \sum_T^{+\infty} \lambda_t^1 f_L(k_t^*, L_t^*) \sum_i l_t^{*i}.$$

Let $\varepsilon > 0$. There exists T such that $\beta^T/(1-\beta) \leq \varepsilon$. Hence, $\sum_T^{+\infty} \lambda_t^1(\eta) \sum_i c_t^{*i} \leq \varepsilon$, $\sum_T^{+\infty} \lambda_t^1(\eta) f_L(k_t^*, L_t^*) \sum_i l_t^{*i} \leq \varepsilon$, for any η.
We now prove that for T large enough, $\sum_T^{+\infty} \lambda_t^1(\eta) f_L(k_t^*, L_t^*) \leq \varepsilon$ for any η. We have

$$\sum_i c_t^{*i} = f(k_t^*, L_t^*) - k_{t+1}^*.$$

Because

$$f(k_t^*, L_t^*) = f(k_t^*, L_t^*) - f(0,0) \geq f_k(k_t^*, L_t^*)k_t^* + f_L(k_t^*, L_t^*)L_t^*,$$

we obtain, using (9),

$$\sum_{t=T}^{T+\tau} \lambda_t^1 \sum_i c_t^{*i} \geq \lambda_T^1 f_k(k_T^*, L_T^*)k_T^* - \lambda_{T+\tau}^1 k_{T+\tau+1}^* + \sum_{t=T}^{T+\tau} \lambda_t^1 f_L(k_t^*, L_t^*)L_t^*.$$

Let $\tau \to +\infty$. Because $\lambda^1 \in \ell^1$, and $k_t^* \leq \max\{k_0, \bar{k}\}, \forall t$, we have

$$\sum_{t=T}^{+\infty} \lambda_t^1 \sum_i c_t^{*i} \geq \lambda_T^1 f_k(k_T^*, L_T^*)k_T^* + \sum_{t=T}^{+\infty} \lambda_t^1 f_L(k_t^*, L_t^*)L_t^* \tag{13}$$

$$\geq \sum_{t=T}^{+\infty} \lambda_t^1 f_L(k_t^*, L_t^*)L_t^* = \sum_{t=T}^{+\infty} \lambda_t^1 f_L(k_t^*, L_t^*) \left(m - \sum_i l_t^{*i}\right)$$

Hence, for T large enough,

$$m \sum_{t=T}^{+\infty} \lambda_t^1 f_L(k_t^*, L_t^*) \leq \sum_{t=T}^{+\infty} \lambda_t^1 \sum_i c_t^{*i} + \sum_{t=T}^{+\infty} \lambda_t^1 f_L(k_t^*, L_t^*) \sum_i l_t^{*i} \leq \varepsilon$$

for any η.

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2. Obviously,

$$\sum_{0}^{+\infty} \lambda_t^1 \sum_i c_t^{*i} + \sum_{0}^{+\infty} \lambda_t^1 f_L(k_t^*, L_t^*) \sum_i l_t^{*i} \leq M_1 = \frac{1}{1-\beta} \sum_i u^i(A, 1) \tag{14}$$

$$\times \sum_{t=0}^{+\infty} \lambda_t^1 f_L(k_t^*, L_t^*) \leq M_2 = \frac{2}{m} \times \frac{1}{1-\beta} \sum_i u^i(A, 1).$$

■

PROPOSITION 7. *Let* $k_0 > 0$. *Let* $(\mathbf{k}^*, \mathbf{c}^*, \mathbf{L}^*, \mathbf{l}^*)$ *solve the Pareto problem associated with* $\eta \in \Delta$. *Take*

$$p_t^* = \lambda_t^1, \ \ w_t^* = \lambda_t^1 f_L(k_t^*, L_t^*) \text{ for any } t$$

and

$$r = \lambda_0^1 [F_k(k_0, 0) + 1 - \delta].$$

Then $\{\mathbf{c}^*, \mathbf{k}^*, \mathbf{L}^*, \mathbf{p}^*, \mathbf{w}^*, r\}$ *is an equilibrium with transfers.*

Proof.

(i) We have

$$\mathbf{c}^* \in (\ell_+^\infty)^m, \mathbf{l}^* \in (\ell_+^\infty)^m, \mathbf{k}^* \in \ell_+^\infty, \mathbf{p}^* \in \ell_+^1, \mathbf{w}^* \in \ell_+^1.$$

From Remark 2, Statement (4), $\mathbf{p}^* \neq \mathbf{0}$, and together with Remark 2, $\mathbf{w}^* \neq \mathbf{0}$.

(ii) We now show that $(\mathbf{c}^{*i}, \mathbf{l}^{*i})$ solves the consumer's problem. Let $(\mathbf{c}^i, \mathbf{l}^i)$ satisfy

$$\sum_{t=0}^{\infty} p_t^* c_t^i + \sum_{t=0}^{\infty} w_t^* l_t^i \leq \sum_{t=0}^{\infty} p_t^* c_t^{*i} + \sum_{t=0}^{\infty} w_t^* l_t^{*i}.$$

Let

$$\Delta = \sum_{t=0}^{\infty} \beta_i^t u^i \left(c_t^{*i}, l_t^{*i}\right) - \sum_{t=0}^{\infty} \beta_i^t u^i \left(c_t^i, l_t^i\right).$$

Because u^i is concave, from Proposition 3, statement (a), we have

$$\Delta \geq \sum_{t=0}^{\infty} \frac{\lambda_t^1}{\eta_i} (c_t^{*i} - c_t^i) + \sum_{t=0}^{\infty} \frac{\lambda_t^1 f_L(k_t^*, L_t^*)}{\eta_i} (l_t^{*i} - l_t^i)$$

$$= \sum_{t=0}^{\infty} \frac{p_t^*}{\eta_i} (c_t^{*i} - c_t^i) + \sum_{t=0}^{\infty} \frac{w_t^*}{\eta_i} (l_t^{*i} - l_t^i) \geq 0.$$

This means that $(\mathbf{c}^{*i}, \mathbf{l}^{*i})$ solves the consumer's problem.

(iii) We now show that $(\mathbf{k}^*, \mathbf{L}^*)$ is the solution to the firm's problem. Because $p_t^* = \lambda_t^1$, $w_t^* = \lambda_t^1 f_L(k_t^*, L_t^*)$, we have

$$\pi^* = \sum_{t=0}^{\infty} \lambda_t^1 [f(k_t^*, L_t^*) - k_{t+1}^*] - \sum_{t=0}^{\infty} \lambda_t^1 f_L(k_t^*, L_t^*) \ L_t^* - rk_0.$$

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Let

$$\Delta_T = \sum_{t=0}^{T} \lambda_t^1 [f(k_t^*, L_t^*) - k_{t+1}^*] - \sum_{t=0}^{T} \lambda_t^1 f_L(k_t^*, L_t^*)\, L_t^* - rk_0$$
$$- \left[\sum_{t=0}^{T} \lambda_t^1 [f(k_t, L_t) - k_{t+1}] - \sum_{t=0}^{T} \lambda_t^1 f_L(k_t^*, L_t^*) L_t - rk_0 \right].$$

By the concavity of f, we get

$$\Delta_T \geq \sum_{t=1}^{T} \lambda_t^1 f_k(k_t^*, L_t^*)(k_t^* - k_t) - \sum_{t=0}^{T} \lambda_t^1 (k_{t+1}^* - k_{t+1})$$
$$= [\lambda_1^1 f_k(k_1^*, L_1^*) - \lambda_0^1](k_1^* - k_1) + \dots$$
$$+ [\lambda_T^1 f_k(k_T^*, L_T^*) - \lambda_{T-1}^1](k_T^* - k_T) - \lambda_T^1 (k_{T+1}^* - k_{T+1}).$$

From Proposition 3, statement (b), we have

$$\Delta_T \geq -\lambda_T^1 (k_{T+1}^* - k_{T+1}) = -\lambda_T^1 k_{T+1}^* + \lambda_T^1 k_{T+1} \geq -\lambda_T^1 k_{T+1}^*.$$

Because $\lambda^1 \in \ell_+^1$, $\sup_T k_{T+1}^* < +\infty$, we have

$$\lim_{T \to +\infty} \Delta_T \geq \lim_{T \to +\infty} - \lambda_T^1 k_{T+1}^* = 0.$$

We have proved that the sequences $(\mathbf{k}^*, \mathbf{L}^*)$ maximize the profit of the firm.

Finally, the market is cleared as the utility function is strictly increasing. ■

Let $k_0 > 0$. From Proposition 4, we define the mapping:

$$\phi_i(\eta) = \sum_{t=0}^{\infty} p_t^*(\eta) c_t^{*i}(\eta) + \sum_{t=0}^{\infty} w_t^*(\eta) l_t^{*i}(\eta) - \sum_{t=0}^{\infty} w_t^*(\eta) - \vartheta^i r k_0 - \alpha^i \pi^*(\eta),$$

where

$$p_t^* = \lambda_t^1,\ w_t^* = \lambda_t^1 f_L(k_t^*, L_t^*),\ \forall t,$$
$$\pi^*(\eta) = \sum_{t=0}^{\infty} p_t^*(\eta)[f(k_t^*(\eta), L_t^*(\eta)) - k_{t+1}^*(\eta)] - \sum_{t=0}^{\infty} w_t^*(\eta) L_t^*(\eta) - rk_0.$$

This mapping ϕ_i is uniformly bounded (see Proposition 6, statement 2).

We can now state our main result.

THEOREM 2. *Assume (U1), (U2), (U3), (F1), (F2), (F3). Let* $k_0 > 0$. *Then there exists* $\bar{\eta} \in \Delta$, $\bar{\eta} >> 0$, *such that* $\phi_i(\bar{\eta}) = 0, \forall i$. *This means that there exists a competitive equilibrium.*

Proof. We first prove that ϕ_i is continuous for any i. Let $(\eta^n) \to \eta$. Because,

$$c_t^{*i}(\eta^n) \to c_t^{*i}(\eta), l_t^{*i}(\eta^n) \to l_t^{*i}(\eta), k_t^*(\eta^n) \to k_t^*(\eta),$$

and if $\sum_j c_t^{*j}(\eta) > 0$ then $p_t^*(\eta^n) \to p_t^*(\eta)$, $w_t^*(\eta^n) \to w_t^*(\eta)$. It remains to be proven that $p_t^*(\eta^n) \to p_t^*(\eta)$, $w_t^*(\eta^n) \to w_t^*(\eta)$ even when $\sum_j c_t^{*j}(\eta) = 0$. Let $\mathcal{T} = \{t : \sum_j c_t^{*j}(\eta) = 0\}$. From the proof in Proposition 6, there exists M such that for any $\eta \in \Delta$,

$$\sum_{t=0}^{+\infty} w_t^*(\eta) = \sum_{t=0}^{+\infty} \lambda_t^1(\eta) f_L(k_t^*, L_t^*) \leq M,$$

and for any $\varepsilon > 0$, there exists T_0 such that, for any $\eta \in \Delta$, for any $T \geq T_0$,

$$\sum_{T}^{+\infty} w_t^*(\eta) = \sum_{T}^{+\infty} \lambda_t^1(\eta) f_L(k_t^*, L_t^*) \leq \varepsilon.$$

These inequalities show that $\{w^*(\eta^n)\}$ is in a relatively compact set of ℓ^1. We can assume that it converges to $(\bar{w}_t) \in \ell^1$. From (12), for $t \in \mathcal{T}, \lambda_t^1(\eta^n) \to \bar{\lambda}_t^1 = \bar{w}_t / f_L(k_t^*, m)$.

When $\sum_j c_0^{*j}(\eta) > 0$, consider T, the first date where $\sum_j c_T^{*j}(\eta) = 0$. For $t = 0, \ldots, T-1$, we have $\lambda_t^1(\eta^n) \to \lambda_t^1(\eta)$. Because $\lambda_T^1(\eta^n) f_L(k_T^*(\eta^n), L_t^*(\eta^n)) = \lambda_{T-1}^1(\eta^n)$, we have $\bar{\lambda}_t^1 f_L(k_T^*(\eta), m) = \lambda_{T-1}^1(\eta)$. From Proposition 4 and relation (12), we have $\bar{\lambda}_T^1 = \lambda_T^1(\eta)$. In other words, $\lambda_T^1(\eta^n) \to \lambda_T^1(\eta)$. By induction, $\lambda_t^1(\eta^n) \to \lambda_t^1(\eta)$ for any $t \geq T$.

Use the same arguments to prove that $\lambda_t^1(\eta^n) \to \lambda_t^1(\eta)$ for any t, when $\sum_j c_0^{*j}(\eta) = 0$.

From these results we get $\bar{w}_t = w_t^*(\eta)$ for any t.

It follows from (13) and (14) in Proposition 6 that for any $\eta \in \Delta$, any T,

$$\frac{\beta^T}{1-\beta} \sum_i u^i(A, 1) \geq \sum_{t=T}^{+\infty} \lambda_t^1 \sum_i c_t^{*i} \geq \sum_{T}^{+\infty} \lambda_t^1 f_L(k_t^*, L_t^*) L_t^*$$

or

$$\frac{2\beta^T}{1-\beta} \sum_i u^i(A, 1) \geq \sum_{t=T}^{+\infty} \lambda_t^1 \sum_i \left[c_t^{*i} + f_L(k_t^*, L_t^*) l_t^{*i}\right] \geq m \sum_{T}^{+\infty} \lambda_t^1 f_L(k_t^*, L_t^*). \tag{15}$$

Let $\varepsilon > 0$. From inequality (15), there exists T such that for any n we have

$$\Bigg|\sum_{t\geq T} p_t^*(\eta^n)c_t^{*i}(\eta^n) + \sum_{t\geq T} w_t^*(\eta^n)l_t^{*i}(\eta^n) - \sum_{t\geq T} w_t^*(\eta^n) - \vartheta^i rk_0$$
$$- \alpha^i \sum_{t\geq T} p_t^*(\eta^n)\sum_i c_t^{*i}(\eta^n) - \sum_{t\geq T} w_t^*(\eta^n)\left[m - \sum_i l_t^{*i}(\eta^n)\right] - rk_0\Bigg| \leq \varepsilon$$

and

$$\Bigg|\sum_{t\geq T} p_t^*(\eta)c_t^{*i}(\eta) + \sum_{t\geq T} w_t^*(\eta)l_t^{*i}(\eta) - \sum_{t\geq T} w^*{}_t(\eta) - \vartheta^i r^*(\eta)k_0$$
$$-\alpha^i \sum_{t\geq T} p^*{}_t(\eta)\sum_i c_t^{*i}(\eta) - \sum_{t\geq T} w^*{}_t(\eta)\left[m - \sum_i l_t^{*i}(\eta)\right] - r^*(\eta)k_0\Bigg| \leq \varepsilon.$$

Consider $t \in \{0, \ldots, T-1\}$. One has $p_t^*(\eta^n) \to p_t^*(\eta)$, $w_t^*(\eta^n) \to w_t^*(\eta)$, $c_t^{*i}(\eta^n) \to c_t^{*i}(\eta)$, $l_t^{*i}(\eta^n) \to l_t^{*i}(\eta)$, $k_t^*(\eta^n) \to k_t^*(\eta)$. Thus, for n large enough, we have $|\phi_i(\eta^n) - \phi_i(\eta)| \leq 3\varepsilon$. The proof that ϕ_i is continuous is complete.

Observe that $\sum_i \phi_i(\eta) = 0$ by Walras law. It follows from Remark 1 (1) that $\eta_i = 0 \Rightarrow \phi_i(\eta) < 0$. Let $\Psi_i(\eta) = \eta_i - \phi_i(\eta)$. We then have $\sum_i \Psi_i(\eta) = 1$ and $\eta_i = 0 \Rightarrow \Psi_i(\eta) > 0$. The mapping $\Psi = (\Psi_1, \ldots, \Psi_m)$ satisfies the inward-boundary fixed point theorem. There exists $\bar{\eta} \in \Delta$, $\bar{\eta} \gg 0$, such that $\Psi(\bar{\eta}) = \bar{\eta}$, or equivalently $\phi_i(\bar{\eta}) = 0, \forall i$. ■

Final Remark. Observe that any equilibrium allocation $(\mathbf{c}^*, \mathbf{l}^*, \mathbf{k}^*)$ satisfies the individual rationality constraint:

$$\sum_{t=0}^{\infty} \beta_i^t u^i(c_t^{*t}, l_t^{*i}) \geq \sum_{t=0}^{\infty} \beta_i^t u^i(0, 1) = \frac{u^i(0,1)}{1-\beta_i}.$$

One can therefore alternatively study the individually rational Pareto optimum problem

$$\max \sum_{i=1}^{m} \eta_i \sum_{t=0}^{\infty} \beta_i^t u^i(c_t^i, l_t^i),$$
$$\text{s.t.} \sum_{i=1}^{m} c_t^i + k_{t+1} \leq f\left(k_t, \sum_{i=1}^{m}(1 - l_t^i)\right), \forall t$$
$$\forall t,\ c_t^i \geq 0,\ l_t^i \geq 0,\ l_t^i \leq 1,\ \forall i, k_t \geq 0,\ \forall t,\ k_0 \text{ given},$$

with the additional individual rationality constraints

$$\sum_{t=0}^{\infty} \beta_i^t u^i(c_t^t, l_t^i) \geq \sum_{t=0}^{\infty} \beta_i^t u^i(0,1) = \frac{u^i(0,1)}{1-\beta_i},\ \forall i = 1, \ldots, m.$$

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We can show, as previously, that any individually rational Pareto optimum is an equilibrium with transfers $\phi(\eta)$, and that there exist $\eta \gg 0$ such that $\phi(\eta) = 0$, i.e., there exists a competitive equilibrium. The proof, however, is more tricky [see the working paper version of this paper, Goenka et al. (2011), for more details].

NOTES

1. They assumed $u(\epsilon, \epsilon)/\epsilon \to +\infty$ as $\epsilon \to 0$ to show $c_t > 0, l_t > 0$ and $u_{cc}/u_c \leq u_{cl}/u_l$ for the proof of $k_t > 0$ for all t.

2. Le Van et al. (2007) assume that the cross partial derivative u^i_{cl} has constant sign, $u^i_c(x, x)$ and $u^i_l(x, x)$ are nonincreasing in x, the production function F is homogenous of degree $\alpha \leq 1$, and $F_{kL} \geq 0$ (Assumptions U4, F4, U5, F5).

3. We relax some important assumptions in the literature. For example, Bewley (1972) assumes that the production set is a convex cone (Theorem 3, p. 525). Bewley (1982) assumes the strict positiveness of derivatives of utility functions on $\mathbf{R}^L_+$ (strict monotonicity assumption, p. 240).

4. For a concave function f defined on $\mathbf{R}^n$, $\partial f(x)$ denotes the subdifferential of f at x.

5. Assumption $f_k(0, 1) > 1$ is equivalent to the Adequacy Assumption in Bewley (1972); see Le Van and Dana (2003, Remark 6.1.1). This assumption is crucial to have equilibrium prices in ℓ^1_+ because it implies that the production set has an interior point. Subsequently, one can use a separation theorem in the infinite-dimensional space to derive Lagrange multipliers.

REFERENCES

Aliprantis, Charalambos D., Donald J. Brown, and Owen Burkinshaw (1990) *Existence and Optimality of Competitive Equilibria*. Heidelberg: Springer.

Becker, Robert A. (1980) On the long-run steady state in a simple dynamic model of equilibrium with heterogeneous households. *Quarterly Journal of Economics* 95, 375–382.

Berge, Claude (1959) *Espaces Topologiques*. Paris: Dunod. [English translation: *Topological Spaces*. Edinburgh: Oliver and Boyd (1963)].

Bewley, Truman F. (1972) Existence of equilibria in economies with infinitely many commodities. *Journal of Economic Theory* 4, 514–540.

Bewley, Truman F. (1982) An integration of equilibrium theory and turpike theory. *Journal of Mathematical Economics* 10, 233–267.

Dana, Rose-Anne and Cuong Le Van (1991) Equilibria of a stationary economy with recursive preferences. *Journal of Optimization Theory and Applications* 71, 289–313.

Dechert, W. Davis (1982) Lagrange multipliers in infinite horizon discrete time optimal control models. *Journal of Mathematical Economics* 9, 285–302.

Florenzano, Monique and Cuong Le Van (2001) *Finite Dimensional Convexity and Optimization*. Heidelberg, Germany: Springer-Verlag.

Goenka, Aditya, Cuong Le Van, and Manh-Hung Nguyen (2011) Existence of Competitive Equilibrium in an Optimal Growth Model with Heterogeneous Agents and Endogeneous Leisure. Working paper CES, Paris.

Le Van, Cuong and Rose-Anne Dana (2003) *Dynamic Programming in Economics*. Dordrecht, The Netherlands: Kluwer Academic.

Le Van, Cuong, Manh-Hung Nguyen, and Yiannis Vailakis (2007) Equilibrium dynamics in an aggregative model of capical accumulation with heterogeneous agents and elastic labor. *Journal of Mathematical Economics* 43, 287–317.

Le Van, Cuong and Cagri Saglam (2004) Optimal growth models and the Lagrange multiplier *Journal of Mathematical Economics* 40, 393–410.

Le Van, Cuong and Yiannis Vailakis (2004) Existence of Competitive Equilibrium in a Single-Sector Growth Model with Elastic Labor. Cahiers de la MSE 2004–123.

Negishi, Takashi (1960) Welfare economics and existence of an equilibrium for a competitive economy. *Metroeconomica* 12, 92–97.

Peleg, Bezalel and Menahem E. Yaari (1970) Markets with countably many commodities. *International Economic Review* 11, 369–377.

Ramsey, Frank P. (1928) A mathematical theory of saving. *Economic Journal* 38, 543–559.