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Integration of Banach-Valued Correspondences

*Nicholas C. Yannelis*

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Integration of Banach-Valued Correspondences

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## ABSTRACT

The purpose of this paper is to study the basic properties of the integral of a Banach-valued correspondence. In particular, we study the convergence, compactness and convexity properties of the Bochner and Gel'fand integrals of a set valued function. The above properties are applied to prove the existence of an equilibrium for an abstract economy with a continuum of agents.





## Table of Contents

1. Introduction
2. Preliminaries
3. Weak Compactness in  $L_p(\mu, X)$
4. Weak Sequential Convergence in  $L_p(\mu, X)$
5. Properties of the Set of Integrable Selections from a Correspondence
6. Properties of the Integral of a Correspondence
7. The Gel'fand Integral
8. Applications

## 1. INTRODUCTION

The classical model of exchange under perfect competition known as the "Arrow-Debreu-McKenzie model" was formulated in terms of a finite set of agents taking prices as given and engaging in sale and purchase of commodities. Aumann (1966) argued that the classical model is clearly at odds with itself as the finitude of agents means that each individual is able to exercise some influence and therefore the assumption of price taking behavior is not sensible. In a path breaking paper, Aumann (1966) resolves this problem by assuming that the set of agents is an atomless measure space and consequently the influence of each agent in the economy as a whole is "negligible." Hence, the "Aumann economy," that is, an economy with an atomless measure space of agents, captures precisely the meaning of perfect competition.

In order to prove the existence of a competitive equilibrium in a perfectly competitive economy, Aumann (1966) faced the following fundamental problem. What is the definition of the aggregate demand set if the set of agents is an atomless measure space? For instance, if we denote the set of agents by  $T$  and denote by  $D(t,p)$  the demand set of agent  $t \in T$ , as prices  $p$ , we know that if  $T$  is finite, the aggregate demand set is given by the summation of the individual demand sets, i.e.,  $\sum_{t \in T} D(t,p)$ . However, if  $T$  is an atomless measure space, then we have to integrate the set  $D(t,p)$ . But what does it mean to integrate a set-valued function? In a seminal paper Aumann (1965) introduced the notion of the integral of a set-valued function (or correspondence) and proved some basic results needed to tackle the problem of the existence of a competitive equilibrium in an economy

with an atomless measure space of agents, and with a finite dimensional commodity space.

However, if one wishes to allow for perfectly competitive economies with an infinite dimensional commodity space, then an extension of the work of Aumann (1965) is required. In particular, from the integration of finite dimensional-valued correspondences we must now pass to integration of Banach-valued correspondences.

The main purpose of this paper is to study the integral of a Banach-valued correspondence and prove some basic theorems needed in general equilibrium and game theory. Results due to Debreu (1967), Datko (1972), Diestel (1977), Hiai-Umegaki (1977), Khan (1982, 1984, 1985), Papageorgiou (1985), Khan-Majumdar (1986), Balder (1988), Yannelis (1988, 1988a, 1989), Rustichini (1989), and Castaing (1988) have drastically influenced the present paper which in a way may be considered as a synthesis of the work of the above authors.

## 2. PRELIMINARIES

### 2.1 Notation

$R^n$  denotes the n-fold Cartesian product of the set of real numbers  $R$ .

$\text{con}A$  denotes the convex hull of the set  $A$ .

$\overline{\text{con}A}$  denotes the closed convex hull of the set  $A$ .

$2^A$  denotes the set of all nonempty subsets of the set  $A$ .

$\emptyset$  denotes the empty set.

$/$  denotes the set of theoretic subtraction.

$\text{dist}$  denotes distance.

$\text{proj}$  denotes projection.

If  $A \subset X$ , where  $X$  is a Banach space,  $\text{cl}A$  denotes the norm closure of  $A$ .

If  $X$  is a linear topological space, its dual is the space  $X^*$  of all continuous linear functionals on  $X$ , and if  $p \in X^*$  and  $x \in X$  the value of  $p$  at  $x$  is denoted either by  $\langle p, x \rangle$  or  $p \cdot x$ .

If  $\{F_n : n=1, 2, \dots\}$  is a sequence of nonempty subsets of a Banach space  $X$ , we will denote by  $s - \text{Ls}F_n$  and  $s - \text{Li}F_n$  the set of its (strong) limit superior and (strong) limit inferior points respectively, i.e.,

$$s - \text{Ls}F_n = \{x \in X : x = s - \lim_{k \rightarrow \infty} x_{n_k}, x_{n_k} \in F_{n_k}, k = 1, 2, \dots\}$$

$$s - \text{Li}F_n = \{x \in X : x = s - \lim_{n \rightarrow \infty} x_n, x_n \in F_n, n = 1, 2, \dots\}.$$

A  $w$  in front of  $\text{Ls}F_n$  ( $\text{Li}F_n$ ) will mean limit superior (limit inferior) with respect to the weak topology  $w(X, X^*)$ .

## 2.2 Definitions

Let  $X$  and  $Y$  be sets. The graph of the set-valued function (or correspondence),  $\phi : X \rightarrow 2^Y$  is denoted by  $G_\phi = \{(x, y) \in X \times Y : y \in \phi(x)\}$ . Let  $(T, \tau, \mu)$  be a complete, finite measure space, and  $X$  be a separable Banach space. The correspondence  $\phi : T \rightarrow 2^X$  is said to have a measurable graph if  $G_\phi \in \tau \otimes \beta(X)$ , where  $\beta(X)$  denotes the Borel  $\sigma$ -algebra on  $X$  and  $\otimes$  denotes product  $\sigma$ -algebra. The correspondence  $\phi : T \rightarrow 2^X$  is said to be lower measurable if for every open subset  $V$  of  $X$ , the set  $\{t \in T : \phi(t) \cap V \neq \emptyset\}$  is an element of  $\tau$ . Recall [see for instance Himmelberg (1975), p. 47 or Debreu (1966), p. 359] that if  $\phi : T \rightarrow 2^X$  has a measurable graph, then  $\phi$  is lower measurable. Furthermore, if  $\phi(\cdot)$  is closed value and lower measurable then

$\phi : T \rightarrow 2^X$  has a measurable graph. A well-known result of Aumann (1967) which will be of fundamental importance in this paper [see also Himmelberg (1975), Theorem 5.2, p. 60], says that if  $(T, \tau, \mu)$  is a complete, finite measure space,  $X$  is a separable metric space and  $\phi : T \rightarrow 2^X$  is a nonempty valued correspondence having a measurable graph, then  $\phi(\cdot)$  admits a measurable selection, i.e., there exists a measurable function  $f : T \rightarrow X$  such that  $f(t) \in \phi(t)$   $\mu$ -a.e.

We now define the notion of a Bochner integrable function. We will follow closely Diestel-Uhl (1977). Let  $(T, \tau, \mu)$  be a finite measure space and  $X$  be a Banach space. A function  $f : T \rightarrow X$  is called simple if there exist  $x_1, x_2, \dots, x_n$  in  $X$  and  $\alpha_1, \alpha_2, \dots, \alpha_n$  in  $\tau$  such that  $f = \sum_{i=1}^n x_i \chi_{\alpha_i}$ , where  $\chi_{\alpha_i}(t) = 1$  if  $t \in \alpha_i$  and  $\chi_{\alpha_i}(t) = 0$  if  $t \notin \alpha_i$ . A function  $f : T \rightarrow X$  is said to be  $\mu$ -measurable if there exists a sequence of simple functions  $f_n : T \rightarrow X$  such that  $\lim_{n \rightarrow \infty} \|f_n(t) - f(t)\| = 0$  for almost all  $t \in T$ . A  $\mu$ -measurable function  $f : T \rightarrow X$  is said to be Bochner integrable if there exists a sequence of simple functions  $\{f_n : n=1, 2, \dots\}$  such that

$$\lim_{n \rightarrow \infty} \int_T \|f_n(t) - f(t)\| d\mu(t) = 0.$$

In this case we define for each  $E \in \tau$  the integral to be  $\int_E f(t) d\mu(t) = \lim_{n \rightarrow \infty} \int_E f_n(t) d\mu(t)$ . It can be shown [see Diestel-Uhl (1977), Theorem 2, p. 45] that, if  $f : T \rightarrow X$  is a  $\mu$ -measurable function then  $f$  is Bochner integrable if and only if  $\int_T \|f(t)\| d\mu(t) < \infty$ . It is important to note that the Dominated Convergence Theorem holds for Bochner integrable functions, in particular, if  $f_n : T \rightarrow X$ , ( $n=1, 2, \dots$ ) is a sequence of

Bochner integrable functions such that  $\lim_{n \rightarrow \infty} f_n(t) = f(t)$   $\mu$ -a.e., and  $\|f_n(t)\| \leq g(t)$   $\mu$ -a.e., where  $g \in L_1(\mu, \mathbb{R})$ , then  $f$  is Bochner integrable and  $\lim_{n \rightarrow \infty} \int_T \|f_n(t) - f(t)\| d\mu(t) = 0$ .

For  $1 \leq p < \infty$ , we denote by  $L_p(\mu, X)$  the space of equivalence classes of  $X$ -valued Bochner integrable functions  $x : T \rightarrow X$  normed by

$$\|x\|_p = \left( \int_T \|x(t)\|^p d\mu(t) \right)^{\frac{1}{p}}.$$

It is a standard result that normed by the functional  $\|\cdot\|_p$  above,  $L_p(\mu, X)$  becomes a Banach space [see Diestel-Uhl (1977), p. 50].

We denote by  $S_\phi^p$  the set of all selections from  $\phi : T \rightarrow 2^X$  that belong to the space  $L_p(\mu, X)$ , i.e.,

$$S_\phi^p = \{x \in L_p(\mu, X) : x(t) \in \phi(t) \mu\text{-a.e.}\}.$$

We will also consider the set  $S_\phi^1 = \{x \in L_1(\mu, X) : x(t) \in \phi(t) \mu\text{-a.e.}\}$ , i.e.,  $S_\phi^1$  is the set of all Bochner integrable selections from  $\phi(\cdot)$ . Using the above set and following Aumann (1965) we can define the integral of the correspondence  $\phi : T \rightarrow 2^X$  as follows:

$$\int_T \phi(t) d\mu(t) = \left\{ \int_T x(t) d\mu(t) : x \in S_\phi^1 \right\}.$$

In the sequel we will denote the above integral by  $\int \phi$ . Recall that the correspondence  $\phi : T \rightarrow 2^X$  is said to be integrally bounded if there exists a map  $h \in L_1(\mu, \mathbb{R})$  such that  $\sup\{\|x\| : x \in \phi(t)\} \leq h(t)$   $\mu$ -a.e. Moreover, note that if  $T$  is a complete measure space,  $X$  is a separable Banach space and  $\phi : T \rightarrow 2^X$  is an integrally bounded, nonempty valued correspondence having a measurable graph, then by the Aumann measurable selection theorem we can conclude that  $S_\phi^1$  is nonempty and therefore

$\int_T \phi(t) d\mu(t)$  is nonempty as well. It should be noted that the measurability of  $\phi$  is a sufficient condition for the nonemptiness of  $\int \phi$ , but it is not necessary. In fact,  $\int \phi$  may be nonempty even if  $\phi$  does not have a measurable graph [see Schechter (1989) for an example to that effect].

A Banach space  $X$  has the Radon-Nikodým Property with respect to the measure space  $(T, \tau, \mu)$  if for each  $\mu$ -continuous vector measure  $G : \tau \rightarrow X$  of bounded variation there exists  $g \in L_1(\mu, X)$  such that  $G(E) = \int_E g(t) d\mu(t)$  for all  $E \in \tau$ . A Banach space  $X$  has the Radon-Nikodým Property (RNP) if  $X$  has the RNP with respect to every finite measure space. Recall now [see Diestel-Uhl (1977, Theorem 1, p. 98)] that if  $(T, \tau, \mu)$  is a finite measure space  $1 \leq p < \infty$ , and  $X$  is a Banach space, then  $X^*$  has the RNP if and only if  $(L_p(\mu, X))^* = L_q(\mu, X^*)$  where  $\frac{1}{p} + \frac{1}{q} = 1$ .

Let  $A_n$ ,  $(n=1, 2, \dots)$  be a sequence of nonempty subsets of a Banach space. Following Kuratowski (1966, p. 339) we say that  $A_n$  converges in  $A$  (written as  $A_n \rightarrow A$ ) if and only if  $s\text{-Li}A_n = s\text{-Ls}A_n = A$ . Also, we say that  $A_n$  converges in the Kuratowski-Mosco sense to  $A$  (written as  $A_n \xrightarrow{K-M} A$ ) if and only if  $s\text{-Li}A_n = w\text{-Ls}A_n = A$ . It may be useful to remind the reader that  $\text{Li}A_n$  and  $\text{Ls}A_n$  are both closed sets and that  $s\text{-Li}A_n \subset s\text{-Ls}A_n$  [see Kuratowski (1966), pp. 336-338].

Let  $X$  be a metric space and  $Y$  be a Banach space. The correspondence  $\phi : X \rightarrow 2^Y$  is said to be upper semicontinuous (u.s.c.) at  $x_0 \in X$ , if for any neighborhood  $N(\phi(x_0))$  of  $\phi(x_0)$ , there exists a neighborhood  $N(x_0)$  of  $x_0$  such that for all  $x \in N(x_0)$ ,  $\phi(x) \subset N(\phi(x_0))$ . We say that  $\phi$  is u.s.c. if  $\phi$  is u.s.c. at every point  $x \in X$ . Recall that this

definition is equivalent to the fact that the set  $\{x \in X : \phi(x) \subset V\}$  is open in  $X$  for every open subset  $V$  of  $Y$  [see for instance Kuratowski (1966), Theorem 3, p. 176].

Let  $\nu$  be a small positive number and let  $B$  be the open unit ball in  $Y$ . The correspondence  $\phi : X \rightarrow 2^Y$  is said to be quasi upper-semicontinuous (q.u.s.c.) at  $x \in X$ , if whenever the sequence  $x_n$ , ( $n=1, 2, \dots$ ) in  $X$  converges to  $x$ , then for some  $n_0$ ,  $\phi(x_n) \subset \phi(x) + \nu B$  for all  $n \geq n_0$ . We say that  $\phi$  is q.u.s.c. if  $\phi$  is q.u.s.c. at every point  $x \in X$ . It can be easily checked that if  $\phi$  is compact valued, quasi upper-semicontinuity implies upper-semicontinuity and vice-versa.

Let now  $P$  and  $X$  be metric spaces. The correspondence  $F : P \rightarrow 2^X$  is said to be lower semicontinuous (l.s.c.) if the sequence  $p_n$ , ( $n=1, 2, \dots$ ) in  $P$  converges to  $p \in P$ , then  $F(p) \subset \text{Li}F(p_n)$ . Finally recall that the correspondence  $F : P \rightarrow 2^X$  is said to be continuous if and only if it is u.s.c. and l.s.c.

### 3. WEAK COMPACTNESS IN $L_p(\mu, X)$

The result below has found several applications in general equilibrium and game theory [see for example Khan (1986), Yannelis (1987) and Yannelis-Rustichini (1988)] and it is known in the literature of economics as Diestel's theorem on weak compactness in  $L_1(\mu, X)$ .

Theorem 3.1: Let  $(T, \tau, \mu)$  be a complete finite measure space,  $X$  be a separable Banach space and  $\phi : T \rightarrow 2^X$  be an integrally bounded, convex, weakly compact and nonempty valued correspondence. Then  $S_\phi^1$  is weakly compact in  $L_1(\mu, X)$ .



Proof: First note that  $(L_1(\mu, X))^* = L_\infty(\mu, X_w^*)$  [see for instance Tulcea-Tulcea (1969)]. Pick an arbitrary  $x \in L_\infty(\mu, X_w^*)$ . If we show that  $x$  attains its supremum on  $S_\phi^1$  the result will follow from James's theorem [James (1964)]. To this end, let

$$\sup_{f \in S_\phi^1} f \cdot x = \sup_{f \in S_\phi^1} \int_{t \in T} (f(t) \cdot x(t)) d\mu(t).$$

By Lemma 1 in Debreu-Schmeidler (1972) or Theorem 2.2 in Hiai-Unegaki (1977) we have that

$$\sup_{f \in S_\phi^1} \int_{t \in T} (f(t) \cdot x(t)) d\mu(t) = \int_{t \in T} \sup_{g \in \phi(t)} (g \cdot x(t)) d\mu(t).$$

Define the correspondence  $\theta : T \rightarrow 2^X$  by

$$\theta(t) = \{y \in \phi(t) : y \cdot x = \sup_{g \in \phi(t)} g \cdot x\}.$$

Since the correspondence  $\phi : T \rightarrow 2^X$  is weakly compact valued we have that  $\theta(t) \neq \emptyset$  for all  $t \in T$ . Define the function  $F : T \times X \rightarrow [-\infty, \infty]$  by  $F(t, y) = y \cdot x - \sup_{g \in \phi(t)} g \cdot x$ . Note that for each fixed  $t \in T$ ,  $F(t, \cdot)$  is

continuous and for each fixed  $y \in X$ ,  $F(\cdot, y)$  is measurable. Hence, by a standard result [see for instance Himmelberg (1975, Theorem 6.1)],  $F(\cdot, \cdot)$  is jointly measurable and consequently the set

$$F^{-1}(0) = \{(t, y) \in T \times X : F(t, y) = 0\} \text{ belongs to } \tau \otimes \beta(X).$$

Since  $\phi(\cdot)$  has a measurable graph, the set  $G_\phi = \{(t, y) \in T \times X : y \in \phi(t)\}$  is an element of  $\tau \otimes \beta(X)$ . Observe that

$$G_\theta = F^{-1}(0) \cap G_\phi.$$

Since  $F^{-1}(0)$  and  $G_\phi$  belong to  $\tau \otimes \beta(X)$  so does  $G_\theta$ , i.e.,  $\theta(\cdot)$  has a measurable graph. By the Aumann measurable selection theorem, there exists a measurable function  $z : T \rightarrow X$  such that  $z(t) \in \theta(t)$   $\mu$ -a.e. Hence  $z \in S_\phi^1$  and

$$\sup_{g \in S_\phi^1} g \cdot x = \int_{t \in T} (z(t) \cdot x(t)) \, d\mu(t) = z \cdot x.$$

Since  $x \in L_\infty(\mu, X_{w^*}^*)$  was arbitrary, we can conclude that every element of  $(L_1(\mu, X))^* = L_\infty(\mu, X_{w^*}^*)$  attains its supremum on  $S_\phi^1$ . This completes the proof of the Theorem.

Remark 3.1: Note that if  $(T, \tau, \mu)$  is a finite measure space, and  $X$  is a Banach space then  $(L_p(\mu, X))^* = L_q(\mu, X_{w^*}^*)$  where  $1 \leq p < \infty$ ,  $\frac{1}{p} + \frac{1}{q} = 1$  [see Tulcea-Tulcea (1969)]. Hence, in Theorem 3.1 we can replace the fact that  $S_\phi^1$  is weakly in  $L_1(\mu, X)$  with the statement that  $S_\phi^p$ , ( $1 \leq p < \infty$ ) is weakly compact in  $L_p(\mu, X)$ .

Bibliographical notes: Theorem 4.1 was proved by Diestel (1977) in a less general form [see also Byrne (1978)]. However, it should be noted that Castaing had earlier proved a related result to that of Diestel's. Also, Datko (1973) proved a version of Diestel's theorem for a reflexive separable Banach space. The proof of Theorem 4.1 is based on the celebrated theorem of James (1964) and it is patterned after that of Khan (1982, 1987) and Papageorgiou (1985). Recently,

Balder (1990) has given an alternative proof of Diestel's theorem using a.e. convergence of arithmetic averages.

#### 4. WEAK SEQUENTIAL CONVERGENCE IN $L_p(\mu, X)$

We begin by proving the following result:

Theorem 4.1: Let  $(T, \tau, \mu)$  be a finite measure space and  $X$  be a separable Banach space. Let  $\{f_\lambda : \lambda \in \Lambda\}$  ( $\Lambda$  is a directed set), be a net in  $L_p(\mu, X)$ ,  $1 \leq p < \infty$  such that  $f_\lambda$  converges weakly to  $f \in L_p(\mu, X)$ . Suppose that for all  $\lambda \in \Lambda$ ,  $f_\lambda(t) \in F(t)$   $\mu$ -a.e., where  $F : T \rightarrow 2^X$  is a weakly compact, integrably bounded, convex, nonempty valued correspondence. Then we can extract a sequence  $\{f_{\lambda_n} : n=1, 2, \dots\}$  from the net  $\{f_\lambda : \lambda \in \Lambda\}$  such that:

- (i)  $f_{\lambda_n}$  converges weakly to  $f$ , and
- (ii)  $f(t) \in \overline{\text{con w-Ls}\{f_{\lambda_n}(t)\}}$   $\mu$ -a.e.

Proof: We begin the proof of Theorem 4.1 by stating the following result of Artstein (1979, Proposition C, p. 280).

Proposition 4.1: Let  $(T, \tau, \mu)$  be a finite measure space and let  $f_n : T \rightarrow R^k$ , ( $n=1, 2, \dots$ ) be a uniformly integrable sequence of functions converging weakly to  $f$ . Then,

$$f(t) \in \text{con w-Ls}\{f_n(t)\} \mu\text{-a.e.}$$

Using Artstein's result we can prove the following proposition.

Proposition 4.2: Let  $(T, \tau, \mu)$  be a finite measure space and  $X$  be a separable Banach space whose dual  $X^*$  has the RNP. Let  $\{f_n: n=1, 2, \dots\}$  be a sequence in  $L_p(\mu, X)$ ,  $1 \leq p < \infty$  such that  $f_n$  converges weakly to  $f \in L_p(\mu, X)$ . Suppose that for all  $n$ ,  $(n=1, 2, \dots)$ ,  $f_n(t) \in F(t)$   $\mu$ -a.e. where  $F: T \rightarrow 2^X$  is a weakly compact nonempty valued correspondence. Then

$$f(t) \in \overline{\text{con w-Ls}\{f_n(t)\}} \mu\text{-a.e.}$$

Proof: Since  $f_n$  converges weakly to  $f$  and  $X^*$  has the RNP, for any  $\psi \in (L_p(\mu, X))^* = L_q(\mu, X^*)$  (where  $\frac{1}{p} + \frac{1}{q} = 1$ ), we have that  $\langle \psi, f_n \rangle = \int_T \langle \psi(t), f_n(t) \rangle d\mu(t)$  converges to  $\langle \psi, f \rangle = \int_T \langle \psi(t), f(t) \rangle d\mu(t)$ . Define the functions  $h_n: T \rightarrow \mathbb{R}$  and  $h: T \rightarrow \mathbb{R}$  by  $h_n(t) = \langle \psi(t), f_n(t) \rangle$  and  $h(t) = \langle \psi(t), f(t) \rangle$  respectively. Since for each  $n$ ,  $f_n(t) \in F(t)$   $\mu$ -a.e. and  $F(\cdot)$  is weakly compact,  $h_n$  is bounded and uniformly integrable. Also, it is easy to check that  $h_n$  converges weakly to  $h$ . In fact, let  $g \in L_\infty(\mu, \mathbb{R})$  and let  $M = \|g\|_\infty$ , then,

$$(4.1) \quad \left| \int_T g(t)(h_n(t) - h(t)) d\mu(t) \right| = \left| \int_T g(t)(\langle \psi(t), f_n(t) \rangle - \langle \psi(t), f(t) \rangle) d\mu(t) \right| \leq M |\langle \psi, f_n \rangle - \langle \psi, f \rangle|$$

and (4.1) can become arbitrarily small since as it was noted above  $\langle \psi, f_n \rangle$  converges to  $\langle \psi, f \rangle$ .

By Proposition 4.1, we have that  $\mu$ -a.e.,  $h(t) \in \text{con w-Ls}\{h_n(t)\} \subset \overline{\text{con w-Ls}\{h_n(t)\}}$ , i.e.,  $\mu$ -a.e.,  $\langle \psi(t), f(t) \rangle \in \overline{\text{con w-Ls}\{\langle \psi(t), f_n(t) \rangle\}} = \langle \psi(t), \overline{\text{con w-Ls}\{f_n(t)\}} \rangle$  and consequently,

$$(4.2) \quad \int_T \langle \psi(t), f(t) \rangle d\mu(t) \in \int_T \langle \psi(t), x(t) \rangle d\mu(t), \text{ where } x(\cdot) \text{ is a selection from } \overline{\text{con w-Ls}} \{f_n(\cdot)\}.$$

It follows from (4.2) that:

$$(4.3) \quad f \in S_{\overline{\text{con w-Ls}}}^P \{f_n\}.$$

To see this, suppose by way of contradiction that  $f \notin S_{\overline{\text{con w-Ls}}}^P \{f_n\}$ , then by the separating hyperplane theorem<sup>1</sup>, there exists

$$\psi \in (L_p(\mu, X))^* = L_q(\mu, X^*), \psi \neq 0 \text{ such that } \langle \psi, f \rangle > \sup\{\langle \psi, x \rangle :$$

$$x \in S_{\overline{\text{con w-Ls}}}^P \{f_n\}\}, \text{ i.e., } \int_T \langle \psi(t), f(t) \rangle d\mu(t) > \int_T \langle \psi(t), x(t) \rangle d\mu(t),$$

where  $x(\cdot)$  is a selection from  $\overline{\text{con w-Ls}} \{f_n(\cdot)\}$ , a contradiction to

(4.2). Hence, (4.3) holds and we can conclude that

$f(t) \in \overline{\text{con w-Ls}} \{f_n(t)\}$   $\mu$ -a.e. This completes the proof of Proposition

4.2.

Remark 4.1: Proposition 4.2 remains true without the assumption that  $X^*$  has the RNP. The proof proceeds as follows: Since  $f_n$  converges weakly to  $f$  we have that  $\langle \phi, f_n \rangle$  converges to  $\langle \phi, f \rangle$  for all  $\phi \in (L_p(\mu, X))^*$ . It follows from a standard result [see for instance Dinculeanu (1973, p. 112)] that  $\phi$  can be represented by a function  $\psi : T \rightarrow X^*$  such that  $\langle \psi, x \rangle$  is measurable for every  $x \in X$  and  $\|\psi\| \in L_q(\mu, \mathbb{R})$ . Hence,  $\langle \phi, f_n \rangle = \int_T \langle \psi(t), f_n(t) \rangle d\mu(t)$  and  $\langle \phi, f \rangle = \int_T \langle \psi(t), f(t) \rangle d\mu(t)$ . Define the functions  $h_n : T \rightarrow \mathbb{R}$  and  $h : T \rightarrow \mathbb{R}$  by  $h_n(t) = \langle \psi(t), f_n(t) \rangle$  and  $h(t) = \langle \psi(t), f(t) \rangle$  respectively. One can now proceed as in the proof of Proposition 4.2 to complete the argument.

We are now ready to complete the proof of Theorem 4.1. Denote the net  $\{f_\lambda : \lambda \in \Lambda\}$  by  $B$ . Since by assumption for all  $\lambda \in \Lambda$ ,  $f_\lambda(t) \in F(t)$   $\mu$ -a.e. where  $F: T \rightarrow 2^X$  is an integrably bounded, weakly compact, convex, nonempty valued correspondence we can conclude that for all  $\lambda \in \Lambda$ ,  $f_\lambda$  lies in the weakly compact set  $S_F^P$  (recall Diestel's theorem on weak compactness, Theorem 3.1). Hence, the weak closure of  $B$ , i.e.,  $w\text{-cl}B$ , is weakly compact. By the Eberlein-Smulian Theorem [see Dunford-Schwartz (1958, p. 430)],  $w\text{-cl}B$  is weakly sequentially compact. Obviously the weak limit of  $f_\lambda$ , i.e.,  $f$ , belongs to  $w\text{-cl}B$ . From Whitley's theorem<sup>2</sup> [Aliprantis-Burkinshaw (1985, Lemma 10.12, p. 155)], we know that if  $f \in w\text{-cl}B$ , then there exists a sequence  $\{f_{\lambda_n} : n=1, 2, \dots\}$  in  $B$  such that  $f_{\lambda_n}$  converges weakly to  $f$ . Since the sequence  $\{f_{\lambda_n} : n=1, 2, \dots\}$  satisfies all the assumptions of Proposition 4.2 and Remark 4.1 we can conclude that  $f(t) \in \overline{\text{con } w\text{-Ls}\{f_{\lambda_n}(t)\}}$   $\mu$ -a.e. This completes the proof of Theorem 4.1.

An immediate conclusion of Theorem 4.1 is the following useful corollary.

Corollary 4.1: Let  $(T, \tau, \mu)$  be a finite measure space and  $X$  be a separable Banach space. Let  $\{f_n : n=1, 2, \dots\}$  be a sequence of functions in  $L_p(\mu, X)$ ,  $1 \leq p < \infty$  such that  $f_n$  converges weakly to  $f \in L_p(\mu, X)$ . Suppose that for all  $n$ ,  $(n=1, 2, \dots)$ ,  $f_n(t) \in F(t)$   $\mu$ -a.e., where  $F : T \rightarrow 2^X$  is a weakly compact, integrably bounded, nonempty valued correspondence. Then

$$f(t) \in \overline{\text{con } w\text{-Ls}\{f_n(t)\}} \quad \mu\text{-a.e.}$$

Footnotes: <sup>1</sup>Note that the set  $S_{\overline{\text{con } w\text{-Ls}\{f_n\}}}^P$  is nonempty. In fact, since  $w\text{-Ls}\{f_n\}$  is lower measurable and nonempty valued so is  $\overline{\text{con } w\text{-Ls}\{f_n\}}$ . Hence,  $\overline{\text{con } w\text{-Ls}\{f_n\}}$  admits a measurable selection (recall the Kuratowski and Ryll-Nardzewski measurable selection theorem). Obviously the measurable selection is also integrable since  $\overline{\text{con } w\text{-Ls}\{f_n\}}$  lies in a weakly compact subset of  $X$ . Therefore, we can conclude that  $S_{\overline{\text{con } w\text{-Ls}\{f_n\}}}^P$  is nonempty.

<sup>2</sup>See also Kelley-Namioka (1963, exercise L, p. 165).

Bibliographical Notes: Theorem 4.1 and its proof are due to Yannelis (1989). Corollary 4.1 generalizes previous results of Artstein (1979) and Khan-Majumdar (1986). A related result to Corollary 4.1 has also been obtained by Balder (1988) and Castaing (1988). Khan-Yannelis (1986) and Ostroy-Zame (1988) have used Corollary 4.1 in order to prove the existence of an equilibrium in economies with a continuum of agents and commodities.

## 5. PROPERTIES OF THE SET OF INTEGRABLE SELECTIONS FROM A CORRESPONDENCE

We begin by proving  $s\text{-Li}$  and  $w\text{-Ls}$  versions of Fatou's Lemma for the set of integrable selections.

Theorem 5.1: Let  $(T, \tau, \mu)$  be a complete finite measure space and let  $X$  be a separable Banach space. If  $\phi_n : T \rightarrow 2^X$ , ( $n=1, 2, \dots$ ) is a

sequence of integrably bounded correspondences having a measurable graph, i.e.,  $G_{\phi_n} \in \tau \otimes \beta(X)$ , then,

$$S_{s-Li \phi_n}^1 \subset s-Li S_{\phi_n}^1.$$

Proof: Let  $x \in S_{s-Li \phi_n}^1$ , i.e.,  $x(t) \in s-Li \phi_n(t) \mu$ -a.e., we must show that  $x \in s-Li S_{\phi_n}^1$ . First note that  $x(t) \in s-Li \phi_n \mu$ -a.e. implies that there exists a sequence  $\{x_n : n=1, 2, \dots\}$  such that  $s\text{-}\lim_{n \rightarrow \infty} x_n(t) = x(t) \mu$ -a.e. and  $x_n(t) \in \phi_n(t) \mu$ -a.e., which is equivalent to the fact that  $\lim_{n \rightarrow \infty} \text{dist}(x(t), \phi_n(t)) = 0 \mu$ -a.e. For each  $n$ , ( $n=1, 2, \dots$ ) define the correspondence  $A_n : T \rightarrow 2^X$  by  $A_n(t) = \{y \in \phi_n(t) : \|y-x(t)\| \leq \text{dist}(x(t), \phi_n(t)) + \frac{1}{n}\}$ . Clearly for all  $n$ , ( $n=1, 2, \dots$ ) and for all  $t \in T$ ,  $A_n(t) \neq \emptyset$ . Moreover,  $A_n(\cdot)$  has a measurable graph. Indeed, the function  $g : T \times X \rightarrow [-\infty, \infty]$  defined by  $g(t,y) = \|y-x(t)\| - \text{dist}(x(t), \phi_n(t))$  is measurable in  $t$  and continuous in  $y$  and therefore by a standard result [see Himmelberg (1975; Theorem 2, p. 378)]  $g(\cdot, \cdot)$  is jointly measurable with respect to the product  $\sigma$ -algebra  $\tau \otimes \beta(X)$ . It is easy to see that:

$$G_{A_n} = \{(t,y) \in T \times X : g(t,y) \leq \frac{1}{n}\} \cap G_{\phi_n} = g^{-1}([-\infty, \frac{1}{n}]) \cap G_{\phi_n}.$$

Since  $\phi_n(\cdot)$  has a measurable graph and  $g(\cdot, \cdot)$  is jointly measurable, we can conclude that  $G_{A_n}$  belongs to  $\tau \otimes \beta(X)$ , i.e.,  $A_n(\cdot)$  has a measurable graph. By the Aumann measurable selection theorem there exists a measurable function  $f_n : T \rightarrow X$  such that  $f_n(t) \in A_n(t) \mu$ -a.e. Since  $x(t) \in s-Li \phi_n(t) \mu$ -a.e.,  $\lim_{n \rightarrow \infty} \text{dist}(x(t), \phi_n(t)) = 0 \mu$ -a.e. which implies that  $\lim_{n \rightarrow \infty} \|f_n(t) - x(t)\| = 0 \mu$ -a.e. Since  $f_n(t) \in \phi_n(t) \mu$ -a.e.



and  $\phi_n(\cdot)$  is integrably bounded, by the dominated convergence theorem [see Diestel-Uhl (1977, p. 45)],  $f_n(\cdot)$  is Bochner integrable, i.e.,  $f_n \in L_1(\mu, X)$ . Hence,  $x \in s\text{-Li } S_{\phi_n}^1$  and this completes the proof of Theorem 5.1.

Theorem 5.2: Let  $(T, \tau, \mu)$  be a finite measure space,  $X$  be a separable Banach space and let  $\phi_n: T \rightarrow 2^X$ ,  $(n=1, 2, \dots)$  be a sequence of nonempty, closed value correspondences such that:

(i) For all  $n$ ,  $(n=1, 2, \dots)$ ,  $\phi_n(t) \subset F(t)$   $\mu$ -a.e., where  $F: T \rightarrow 2^X$  is an integrably, bounded weakly compact, convex, nonempty-valued correspondence. Then,

$$w\text{-Ls } S_{\phi_n}^1 \subset S_{\overline{\text{con}} w\text{-Ls}\phi_n}^1.$$

Moreover, assume that  $w\text{-Ls}\phi_n(\cdot)$  is closed and convex valued. Then,

$$w\text{-Ls } S_{\phi_n}^1 \subset S_{w\text{-Ls}\phi_n}^1.$$

Proof: Let  $x \in w\text{-Ls } S_{\phi_n}^1$ , i.e., there exists  $x_k \in S_{\phi_{n_k}}^1$ ,  $(k=1, 2, \dots)$  such that  $x_k$  converges weakly to  $x$ . We wish to know that  $x \in S_{\overline{\text{con}} w\text{-Ls}\phi_n}^1$ . Since  $x_k$  converges weakly to  $x$  and  $x_k$  lies in a weakly compact set, it follows from Proposition 4.2 that  $x(t) \in \overline{\text{con } w\text{-Ls}\{x_k(t)\}}$   $\mu$ -a.e. and therefore  $x(t) \in \overline{\text{con } w\text{-Ls}\phi_n(t)}$   $\mu$ -a.e. Since by assumption for each  $n$ ,  $\phi_n(\cdot)$  lies in the integrably bounded convex set  $F(\cdot)$ , we can conclude that  $x \in S_{\overline{\text{con}} w\text{-Ls}\phi_n}^1$ . This completes the proof of the fact that:

$$(5.1) \quad w\text{-Ls } S_{\phi_n}^1 \subset S_{\overline{\text{con}} w\text{-Ls}\phi_n}^1.$$

Since  $w\text{-Ls}\phi_n(\cdot)$  is closed and convex (hence weakly closed) we have that  $w\text{-Ls}\phi_n(\cdot) = \overline{\text{con } w\text{-Ls}\phi_n(\cdot)}$  and therefore,

$$(5.2) \quad S_{w\text{-Ls}\phi_n}^1 = S_{\overline{\text{con } w\text{-Ls}\phi_n}}^1.$$

Combining now (5.1) and (5.2) we can conclude that  $w\text{-Ls } S_{\phi_n}^1 \subset S_{w\text{-Ls}\phi_n}^1$ . This completes the proof of the theorem.

Combining Theorems 5.1 and 5.2 we can obtain the following dominated convergence result for the set of integrable selections from a correspondence.

Corollary 5.1: Let  $(T, \tau, \mu)$  be a complete finite measure space and  $X$  be a separable Banach space. Let  $\phi_n: T \rightarrow 2^X$  ( $n=1, 2, \dots$ ) be a sequence of closed valued and lower measurable correspondences such that:

(i) For each  $n$ , ( $n=1, 2, \dots$ ),  $\phi_n(t) \subset F(t)$   $\mu$ -a.e., where  $F: T \rightarrow 2^X$  is an integrably bounded weakly compact, convex, nonempty valued correspondence,

(ii)  $\phi_n(t) \xrightarrow{K-M} \phi(t)$   $\mu$ -a.e., and

(iii)  $\phi(\cdot)$  is convex valued.

Then

$$S_{\phi_n}^1 \xrightarrow{K-M} S_{\phi}^1.$$

Proof: First note that since for each  $n$ , ( $n=1, 2, \dots$ )  $\phi_n(\cdot)$  is closed valued and lower measurable,  $G_{\phi_n} \in \tau \otimes \beta(X)$ , i.e.,  $\phi_n(\cdot)$  has a measurable graph and so does  $s\text{-Li } \phi_n(\cdot)$ . Now if  $\phi(t) = s\text{-Li } \phi_n(t) = w\text{-Ls } \phi_n(t)$   $\mu$ -a.e., it follows from Theorems 5.1 and 5.2 that:

$$S_{\phi}^1 = S_{s-Li\phi_n}^1 \subset s-LiS_{\phi_n}^1 \subset w-Ls S_{\phi_n}^1 \subset S_{w-Ls\phi_n}^1 = S_{\phi}^1.$$

Therefore

$$S_{\phi}^1 = s-Li S_{\phi_n}^1 = w-Ls S_{\phi_n}^1,$$

and we can conclude that  $S_{\phi_n}^1 \xrightarrow{K-M} S_{\phi}^1$ . This completes the proof of the Corollary.

The lemma below will be used to prove Theorem 5.3.

Lemma 5.1: Let  $(T, \tau, \mu)$  be a complete finite measure space,  $X$  be a separable Banach space and  $F : T \rightarrow 2^X$  be a nonempty closed valued and lower measurable correspondence. Let  $\{f_i : i=1, 2, \dots\}$  be a sequence in  $S_F^p$ , ( $1 \leq p < \infty$ ) such that  $F(t) = cl\{f_i(t) : i=1, 2, \dots\}$   $\mu$ -a.e. Then, for each  $f \in S_F^p$  and  $\delta > 0$ , there exists a finite measurable partition  $\{A_1, A_2, \dots, A_m\}$  of  $(T, \tau)$  such that

$$\|f - \sum_{i=1}^m \chi_{A_i} f_i\|_p < \delta.$$

Proof: Consider a strictly positive  $v \in L_1(\mu, \mathbb{R})$  such that  $\int_{t \in T} v(t) d\mu(t) < \delta^p/3$ . We can find a countable measurable partition  $\{B_i\}$  of  $(T, \tau)$  such that:

$$\|f(t) - f_i(t)\|_p < v(t), \text{ for almost all } t \in B_i, i \geq 1.$$

Pick an integer  $m$  so that

$$\sum_{i=m+1}^{\infty} \int_{B_i} \|f(t)\|_p \, d\mu(t) < (\delta/2)^p/3,$$

$$\sum_{i=m+1}^{\infty} \int_{B_i} \|f_1(t)\|_p \, d\mu(t) < (\frac{\delta}{2})^p/3,$$

and define a measurable partition  $\{A_1, \dots, A_m\}$  as follows:

$$A_1 = B_1 \cup \left( \bigcup_{i=m+1}^{\infty} B_i \right), \quad A_j = B_j \text{ for } j=2, \dots, m.$$

Then it can be easily seen that:

$$\begin{aligned} \|f - \sum_{i=1}^m \chi_{A_i} f_i\|_p &= \sum_{i=1}^m \int_{B_i} \|f(t) - f_i(t)\|_p \, d\mu(t) + \sum_{i=m+1}^{\infty} \int_{B_i} \|f(t) - f_1(t)\|_p \, d\mu(t) \\ &\leq \int_T v(t) \, d\mu(t) + \sum_{i=m+1}^{\infty} 2^p \int_{B_i} (\|f(t)\|_p + \|f_1(t)\|_p) \, d\mu(t) < \delta. \end{aligned}$$

Theorem 5.3: Let  $(T, \tau, \mu)$  be a complete finite measure space,  $X$  be a separable Banach space and  $F: T \rightarrow 2^X$  be a closed, nonempty valued and lower measurable correspondence. Suppose that  $S_F^p$ ,  $(1 \leq p < \infty)$  is non-empty. Then

$$S_{\overline{\text{con}} F}^p = \overline{\text{con}} S_F^p.$$

Proof: Define the correspondence  $\tilde{F}: T \rightarrow 2^X$  by  $\tilde{F}(t) = \overline{\text{con}} F(t)$ . It can be easily checked that  $\tilde{F}(\cdot)$  is lower measurable and obviously closed and convex valued. Moreover,  $S_{\tilde{F}}^p$  is closed and convex. Clearly,  $\overline{\text{con}} S_F^p \subset S_{\overline{\text{con}} F}^p$  since  $S_F^p \subset S_{\overline{\text{con}} F}^p$ . To prove that  $S_{\overline{\text{con}} F}^p \subset \overline{\text{con}} S_F^p$ , consider the sequence  $\{f_i : i=1, 2, \dots\}$  in  $S_F^p$  where  $\text{cl}\{f_i(t) : i=1, 2, \dots\} = F(t)$   $\mu$ -a.e. Define the set

$$U = \{g: \sum_{i=1}^n \lambda_i f_i, \lambda_i \geq 0, \text{ rational}, \sum_{i=1}^n \lambda_i = 1, n \geq 1\}.$$

Observe that  $U$  is a countable subset of  $S_{\text{con } F}^P$  and  $\overline{\text{con } F(t)} = \text{cl}\{g(t): g \in U\}$   $\mu$ -a.e. It follows from Lemma 5.1 that for each  $f \in S_{\text{con } F}^P$  and for each  $\delta > 0$  we can find a finite measurable partition  $\{A_1, A_2, \dots, A_m\}$  of  $(T, \tau)$  and functions  $g_1, g_2, \dots, g_m$  in  $U$  such that:

$$\|f - \sum_{k=1}^m \chi_{A_k} g_k\|_p < \delta.$$

We can now find an integer  $n$  so that, for

$$1 \leq k \leq m, g_k = \sum_{i=1}^n \lambda_{ki} f_i \text{ where } \lambda_{ki} \geq 0, \sum_{i=1}^n \lambda_{ki} = 1.$$

Observe that:

$$\begin{aligned} \sum_{k=1}^m \chi_{A_k} g_k &= \sum_{k=1}^m \chi_{A_k} \left( \sum_{i=1}^n \lambda_{ki} f_i \right) \\ &= \sum_{(i_1, \dots, i_m)} (\lambda_{1i_1}, \dots, \lambda_{mi_m}) \left( \sum_{k=1}^m \chi_{A_k} f_{i_k} \right), \end{aligned}$$

where  $(i_1, \dots, i_m)$  is taken for  $1 \leq i_k \leq n, k=1, \dots, m$ . Therefore,  $\sum_{k=1}^m \chi_{A_k} g_k$  is a convex combination of functions in  $S_F^P$  and we can conclude that  $f \in \overline{\text{con } S_F^P}$ . This completes the proof of Theorem 5.3.

Below we consider correspondences of two variables and assume that they are measurable in the one variable and u.s.c. or l.s.c. in the other. We then ask the question as to whether the set of all integrable selections of the correspondence is either u.s.c. or l.s.c.

Theorem 5.4: Let  $(T, \tau, \mu)$  be a complete, finite measure space,  $P$  be a metric space and  $X$  be a separable Banach space. Let  $\psi : T \times P \rightarrow 2^X$  be a nonempty valued, integrably bounded correspondence, such that for each fixed  $t \in T$ ,  $\psi(t, \cdot)$  is q.u.s.c. and for each fixed  $p \in P$ ,  $\psi(\cdot, p)$  has a measurable graph. Then

$$S_{\psi}^1(\cdot) \text{ is q.u.s.c.}$$

Proof: Let  $\tilde{B}$  be the open unit ball in  $L_1(p, X)$  and  $v$  be a small positive number. We must show that if  $\{p_n : n=1, 2, \dots\}$  is a sequence in  $P$  converging to  $p \in P$ , then for a suitable  $n_0$ ,  $S_{\psi}^1(p_n) \subset S_{\psi}^1(p) + v\tilde{B}$  for all  $n \geq n_0$ .

We begin by finding the suitable  $n_0$ . Since for each fixed  $t \in T$ ,  $\psi(t, \cdot)$  is q.u.s.c. we can find a minimal  $M_t$  such that

$$(5.3) \quad \psi(t, p_n) \subset \psi(t, p) + \delta B \text{ for all } n \geq M_t,$$

$$\text{where } \delta = \frac{v}{3\mu(T)}.$$

We now show that  $M_t$  is a measurable function of  $t$ . However, first we make a few observations. By assumption for each fixed  $p$  and  $n$ ,  $G_{\psi(\cdot, p_n) + \delta B} \in \tau \otimes \beta(X)$  and so does  $(G_{\psi(\cdot, p_n) + \delta B})^c$ , (where  $S^c$  denotes the complement of the set  $S$ ). It is easy to see that

$$G_{\psi(\cdot, p)} \cap (G_{\psi(\cdot, p_n) + \delta B})^c \in \tau \otimes \beta(X). \text{ Therefore, the set}$$

$$U = \{(t, x) \in T \times X : (t, x) \in G_{\psi(\cdot, p)} \cap (G_{\psi(\cdot, p_n) + \delta B})^c\}$$

belongs to  $\tau \otimes \beta(X)$ .

It follows from the projection theorem [see for instance Hildenbrand (1974), p. 44] that

$$\text{proj}_T(U) \in \tau.$$

Notice that,

$$\begin{aligned} \text{proj}_T(U) &= \{t \in T : \psi(t, p) \in \psi(t, p_n) + \delta B\} \\ &= \{t \in T : \psi(t, p) / (\psi(t, p_n) + \delta B) \neq \emptyset\}. \end{aligned}$$

By virtue of the measurability of the above set we can now conclude that  $M_t$  is a measurable function of  $t$ . In particular, simply notice that,

$$\{t \in T : M_t = m\} = \bigcap_{n \geq m} \{t \in T : \psi(t, p_n) \in \psi(t, p) + \delta B\} \cap \{t \in T : \psi(t, p_{m-1}) \notin \psi(t, p) + \delta B\}.$$

We are now in a position to choose the desired  $n_0$ . Since  $\psi(\cdot, \cdot)$  is integrably bounded there exists  $h \in L_1(\mu, \mathbb{R})$  such that for almost all  $t \in T$ ,  $\sup\{\|x\| : x \in \psi(t, p)\} \leq h(t)$  for each  $p \in P$ .

Choose  $\delta_1$  such that if  $\mu(S) < \delta_1$ , ( $S \subset T$ ), then  $\int_S h(t) d\mu(t) < \frac{\nu}{3}$ . Since  $M_t$  is a measurable function of  $t$ , we can choose  $n_0$  such that  $\mu(\{t \in T : M_t \geq n_0\}) < \delta_1$ . This is the desired  $n_0$ . Let  $n \geq n_0$  and  $y \in S_\psi^1(p_n)$ . We must show that  $y \in S_\psi^1(p) + \tilde{\nu}B$ .

By assumption, for each fixed  $p \in P$ ,  $\psi(\cdot, p)$  has a measurable graph and  $\psi(\cdot, \cdot)$  is nonempty valued. Hence, by the Aumann measurable selection theorem there exists a measurable function  $f_1 : T \rightarrow X$  such that  $f_1(t) \in \psi(t, p)$   $\mu$ -a.e. Define the correspondence  $\phi : T \rightarrow 2^X$  by  $\phi(t) = (\{y(t)\} + \delta B) \cap \psi(t, p)$ . It follows from (5.3) that for all

$t \in T_0 = \{t : M_t \leq n_0\}$ ,  $\theta(t) \neq \emptyset$ . Moreover,  $\theta(\cdot)$  has a measurable graph. Another application of the Aumann measurable selection theorem allows us to guarantee the existence of a measurable function  $f_2 : T \rightarrow X$  such that  $f_2(t) \in \theta(t)$   $\mu$ -a.e. Define  $f : T \rightarrow X$  by

$$f(t) = \begin{cases} f_1(t) & \text{for } t \notin T_0 \\ f_2(t) & \text{for } t \in T_0. \end{cases}$$

Then  $f(t) \in \psi(t, p)$   $\mu$ -a.e. and since  $\psi(\cdot, \cdot)$  is integrably bounded we can conclude that  $f \in S_\psi^1(p)$ . If we show that  $\|f - y\| < \nu$  then  $y \in S_\psi^1(p) + \tilde{\nu}B$  and we will be done. But this is easy to see. We have

$$\begin{aligned} \|f - y\| &= \int_{T/T_0} \|f_1(t) - y(t)\| d\mu(t) + \int_{T_0} \|f_2(t) - y(t)\| d\mu(t) \\ &< 2 \int_{T/T_0} h(t) d\mu(t) + \int_{T_0} \delta d\mu(t) \\ &< \frac{2\nu}{3} + \delta\mu(T) = \frac{2\nu}{3} + \frac{\nu}{3\mu(T)} \cdot \mu(T) = \nu. \end{aligned}$$

This completes the proof of the theorem.

Remark 5.1: If in addition to the assumptions of Theorem 5.4, it is assumed that  $S_\psi^1(\cdot)$  is compact valued, then we can conclude that  $S_\psi^1(\cdot)$  is u.s.c. Moreover, by adding in Theorem 5.3 the assumption that  $\psi(\cdot, \cdot)$  is convex valued and that for all  $(t, p) \in T \times P$ ,  $\psi(t, p) \subset K$  where  $K$  is a weakly compact, convex, nonempty subset of  $X$ , then it follows from Theorem 3.1 that  $S_\psi^1(\cdot)$  is weakly compact valued and we can conclude that  $S_\psi^1(\cdot)$  is weakly u.s.c., i.e., the set  $\{p \in P : S_\psi^1(p) \subset V\}$  is open in  $P$  for every weakly open subset  $V$  of  $X$ .



Theorem 5.5: Let  $(T, \tau, \mu)$  be a complete, finite separable measure space,  $P$  be a metric space and  $X$  be a separable Banach space. Let  $\psi : T \times P \rightarrow 2^X$  be a nonempty, closed, convex valued correspondence such that:

- (i) for each fixed  $t \in T$ ,  $\psi(t, \cdot)$  is weakly u.s.c.
- (ii) for all  $(t, p) \in T \times P$ ,  $\psi(t, p) \subset K(t)$  where  $K : T \rightarrow 2^X$  is an integrably bounded, weakly compact and nonempty valued correspondence.

Then

$S_\psi^1(\cdot)$  is weakly u.s.c.

Proof: First note that by Theorem 3.1  $S_K^1$  is weakly compact in  $L_1(\mu, X)$ . Since for each  $p \in P$ ,  $S_\psi^1(p)$  is a weakly closed subset of  $S_K^1$ , it is weakly compact. Since the measure space  $(T, \tau, \mu)$  is separable and  $X$  is a separable Banach space,  $L_1(\mu, X)$  is separable. Hence,  $S_K^1$  is metrizable as it is a weakly compact subset of  $L_1(\mu, X)$  [Dunford-Schwartz (1958, Theorem V.6.3, p. 434)]. Consequently, in order to show that  $S_\psi^1(\cdot)$  is weakly u.s.c., it suffices that to show that  $S_\psi^1(\cdot)$  has a weakly closed graph, i.e., if  $\{p_n : n=1, 2, \dots\}$  is a sequence in  $P$  converging to  $p \in P$ , then

$$(5.1) \quad w\text{-}Ls S_\psi^1(p_n) \subset S_\psi^1(p).$$

To this end let  $x \in w\text{-}Ls S_\psi^1(p_n)$ , i.e., there exists  $x_k$ , ( $k=1, 2, \dots$ ) in  $L_1(\mu, X)$  such that  $x_k$  converges weakly to  $x \in L_1(\mu, X)$ , and  $x_k(t) \in \psi(t, p_{n_k})$   $\mu$ -a.e., we must show that  $x \in S_\psi^1(p)$ . It follows Theorem 4.1 that  $x(t) \in \overline{\text{con}w\text{-}Ls\{x_k(t)\}}$   $\mu$ -a.e. and therefore,

$$(5.4) \quad x(t) \in \overline{\text{con} w\text{-Ls}\psi(t, p_n)} \quad \mu\text{-a.e.}$$

Since for each fixed  $t \in T$ ,  $\psi(t, \cdot)$  has a weakly closed graph we have that:

$$(5.5) \quad w\text{-Ls}\psi(t, p_n) \subset \psi(t, p) \quad \mu\text{-a.e.}$$

Combining (5.2) and (5.3) and taking into account the fact that  $\psi$  is convex valued we have that  $x(t) \in \psi(t, p) \quad \mu\text{-a.e.}$  Since  $\psi$  is integrably bounded, we can conclude that  $x \in S_{\psi}^1(p)$ . This completes the proof of Theorem 5.5.

Alternatively, Theorem 5.5 can be proved by means of the Mazur lemma. As noted above, it suffices to show that  $S_{\psi}^1(\cdot)$  has a weakly closed graph. To this end let  $(p_n, y_n) \in G_{S_{\psi}^1}$  be a sequence such that  $p_n$  converges (in the metric topology) to  $p$  and  $y_n$  converges weakly to  $y$ . We must show that  $y \in S_{\psi}^1(p)$ . Since  $y_n \in S_{\psi}^1(p_n)$ , we have that  $y_n(t) \in \psi(t, p_n) \quad \mu\text{-a.e.}$  By Mazur's lemma there exists  $z_n(\cdot) \in \text{con} \bigcup_{n_0 \geq n} y_{n_0}(\cdot)$  such that  $z_n(\cdot)$  converges in norm to  $y(\cdot)$ .

Without loss of generality we may assume (otherwise pass to a subsequence) that  $z_n(t)$  converges in norm to  $y(t)$  for all  $t \in T/S$ , where  $S$  is a set of measure zero. Fix  $t \in T/S$ . Since by assumption  $\psi(t, \cdot)$  is weakly u.s.c. for every small positive number  $\delta$ , there exists  $n$  such that for all  $n_0 \geq n$ ,  $\psi(t, p_{n_0}) \subset \psi(t, p) + \delta B$ , where  $B$  is the open unit ball in  $X$ . But then  $\text{con} \bigcup_{n_0 \geq n} \psi(t, p_{n_0}) \subset \psi(t, p) + \delta B$  and consequently  $y(t) \in \psi(t, p) + \delta B$ . Hence,  $y(t) \in \psi(t, p)$  by letting  $\delta$  converge to zero. Since  $t$  was arbitrary,  $y(t) \in \psi(t, p) \quad \mu\text{-a.e.}$  Finally, since

$\psi(\cdot)$  is integrably bounded, we can conclude that  $y \in S_{\psi}^1(p)$ . This completes the proof.

Theorem 5.6: Let  $(T, \tau, \mu)$  be a complete, finite measure space,  $X$  be a separable Banach space and  $P$  be a metric space. Let  $\phi : T \times P \rightarrow 2^X$  be an integrably bounded correspondence such that for each fixed  $t \in T$ ,  $\phi(t, \cdot)$  is l.s.c. and for each fixed  $p \in P$ ,  $\phi(\cdot, p)$  has a measurable graph. Then

$$S_{\phi}^1(\cdot) \text{ is l.s.c.}$$

Proof: Let  $\{p_n : n=1, 2, \dots\}$  be a sequence in  $P$  converging to  $p \in P$ . We must show that  $S_{\phi}^1(p) \subset \text{Li}S_{\phi}^1(p_n)$ . Since by assumption for each fixed  $t \in T$ ,  $\phi(t, \cdot)$  is l.s.c. we have that  $\phi(t, p) \subset \text{Li}\phi(t, p_n)$  for all  $t \in T$ , and therefore,

$$(5.6) \quad S_{\phi}^1(p) \subset S_{\text{Li}\phi}^1(p_n).$$

It follows now from Theorem 5.1 that (5.6) can be written as:

$$S_{\phi}^1(p) \subset S_{\text{Li}\phi}^1(p_n) \subset \text{Li}S_{\phi}^1(p_n).$$

Hence,

$$S_{\phi}^1(\cdot) \text{ is l.s.c.}$$

The Corollary below follows directly from Theorems 5.4, 5.6 and Remark 5.1.

Corollary 5.6: Let  $(T, \tau, \mu)$  be a complete, finite measure space,  $P$  be a metric space and  $X$  be a separable Banach space. Let  $\psi : T \times P \rightarrow 2^X$  be an integrably bounded, nonempty valued correspondence such that for each fixed  $p \in P$ ,  $\psi(\cdot, p)$  has a measurable graph and for each fixed  $t \in T$ ,  $\psi(t, \cdot)$  is continuous. Moreover, suppose that  $S_{\psi}^1(\cdot)$  is compact valued. Then

$S_{\psi}^1(\cdot)$  is continuous.

Bibliographical Notes. Theorems 5.1, 5.2 and Corollary 5.1 are taken from Yannelis (1989). Theorem 5.3 and its proof is due to Hiai-Umegaki (1977). Theorems 5.4 and 5.6 are variations of some results given in Yannelis (1988a). The proof of Theorem 5.5 is taken from Yannelis (1988a). The alternative proof of Theorem 5.5 is due to Khan-Papageorgiou (1988).

## 6. PROPERTIES OF THE INTEGRAL OF A CORRESPONDENCE

In this section we present an infinite-dimensional generalization of the work of Aumann (1965).

Theorem 6.1: Let  $(T, \tau, \mu)$  be a finite measure space and  $X$  be a separable Banach space. Let  $\phi : T \rightarrow 2^X$  be a correspondence satisfying the following condition:

(i)  $\phi(t) \subset K(t)$   $\mu$ -a.e., where  $K : T \rightarrow 2^X$  is an integrably bounded, weakly compact, convex, nonempty valued correspondence.

Then  $\overline{\int \text{con} \phi}$  is weakly compact.

Proof: Note that since  $\overline{\text{con}\phi}(\cdot)$  is (norm) closed and convex so is  $S_{\overline{\text{con}\phi}}^1$ . It is a consequence of the Separation Theorem that the weak and norm topologies coincide on closed convex sets. Thus,  $S_{\overline{\text{con}\phi}}^1$  is weakly closed. Since  $S_{\overline{\text{con}\phi}}^1$  is a subset of the set  $S_K^1$  and the latter set is weakly compact in  $L_1(\mu, X)$  (recall Theorem 3.1), we can conclude that  $S_{\overline{\text{con}\phi}}^1$  is weakly compact. Define the mapping  $\psi: L_1(\mu, X) \rightarrow X$  by  $\psi(x) = \int_{t \in T} x(t) d\mu(t)$ . Certainly  $\psi$  is linear and norm continuous. By Theorem 15 in Dunford-Schwartz (1958, p. 422),  $\psi$  is also weakly continuous. Hence,  $\psi(S_{\overline{\text{con}\phi}}^1) = \{(\psi(x): x \in S_{\overline{\text{con}\phi}}^1)\} = \overline{\int \text{con}\phi}$  is weakly compact. This completes the proof of the Theorem.

Theorem 6.2: Let  $(T, \tau, \mu)$  be a finite atomless measure space,  $X$  be a Banach space and  $\phi: T \rightarrow 2^X$  be a correspondence. Then  $\text{cl}\int\phi$  is convex.

Proof: Let  $x, y$  be elements of  $\text{cl}\int\phi$ , we must show that for any  $\delta > 0$  and  $\lambda \in (0, 1)$  there exists  $z \in \text{cl}\int\phi$  such that  $\|z - (\lambda x + (1-\lambda)y)\| < \delta$ . Fix  $\delta > 0$  and choose  $x_\delta, y_\delta$  in  $\int\phi$ , such that  $\|x - x_\delta\| < \delta/2$  and  $\|y - y_\delta\| < \delta/2$ . By the definition of the integral of the set-valued function  $\phi$ , we have that there exist  $h, g$  in  $S_\phi^1$  such that

$$(\int h, \int g) = (x_\delta, y_\delta).$$

Define the vector measure  $V: \tau \rightarrow X \times X$  by

$$V(S) = (\int_S h, \int_S g).$$

Since the measure space  $(T, \tau, \mu)$  is atomless it follows from Uhl's theorem [see for instance Uhl (1969) or Diestel-Uhl (1977, p. 266)]<sup>1</sup> that the norm closure of  $V$  is convex. Note that  $V(\emptyset) = (0,0)$  and  $V(T) = (\int_T h, \int_T g)$ . Hence, we can find  $\Omega \in \tau$  such that

$$\|V(\Omega) - \lambda V(T)\| < \delta/2.$$

Define the function  $z : T \rightarrow X$  by

$$z(t) = \begin{cases} h(t) & \text{if } t \in \Omega \\ g(t) & \text{if } t \notin \Omega. \end{cases}$$

Then  $z = \int z(t) d\mu(t) \in \int \phi$  and it can be easily checked that

$$\|z - (\lambda x + (1-\lambda)y)\| \leq \|z - (\lambda x_\delta + (1-\lambda)y_\delta)\| + \lambda \|x_\delta - x\| + (1-\lambda) \|y_\delta - y\| < \delta.$$

This completes the proof of Theorem 6.2.

Define the mapping  $\pi : T \rightarrow X$  by  $\pi(x) = \int_{t \in T} x(t) d\mu(t)$ . Note that

the integral of the correspondence  $\phi : T \rightarrow 2^X$  is  $\pi(S_\phi^1) = \{\pi(x) : x \in S_\phi^1\}$ .

With this observation in mind the reader can easily see that the result below is an immediate conclusion of Theorems 5.3, 6.1 and 6.2.

Theorem 6.3: Let  $(T, \tau, \mu)$  be a finite atomless measure space and  $X$  be a separable Banach space. Suppose that the correspondence  $\phi : T \rightarrow 2^X$  satisfies assumption (i) of Theorem 6.1. Then

$$\overline{\int \phi} = \int \overline{\text{con} \phi} = \text{cl} \int \phi.$$

The results below are w-Ls and s-Li versions of the Fatou lemma and follow directly from Theorems 5.1 and 5.2 respectively.

Theorem 6.4: Let  $(T, \tau, \mu)$  be a complete, finite measure space and  $X$  be a separable Banach space. If  $\phi_n: T \rightarrow 2^X$ ,  $(n=1, 2, \dots)$  is a sequence of integrably bounded correspondences having a measurable graph, i.e.,  $G_{\phi_n} \in \tau \otimes \beta(X)$ , then

$$\int s\text{-Li} \phi_n \subset s\text{-Li} \int \phi_n.$$

Theorem 6.5: Let  $(T, \tau, \mu)$  be a finite measure space, and  $X$  be a separable Banach space. Let  $\phi_n: T \rightarrow 2^X$ ,  $(n = 1, 2, \dots)$  be a sequence of nonempty closed valued correspondences such that:

- (i) For all  $n$ ,  $(n=1, 2, \dots)$ ,  $\phi_n(t) \subset K(t)$   $\mu$ -a.e., where  $K: T \rightarrow 2^X$  is an integrably bounded, weakly compact, convex, nonempty-valued correspondence.

Then

$$w\text{-Ls} \int \phi_n \subset cl \int w\text{-Ls} \phi_n.$$

Furthermore, if  $w\text{-Ls} \phi_n(\cdot)$  is closed and convex valued then

$$w\text{-Ls} \int \phi_n \subset \int w\text{-Ls} \phi_n.$$

As a corollary of Theorems 6.4 and 6.5 and we obtain a Lebesgue-Aumann-type dominated convergence result for the integral of a correspondence.<sup>2</sup>

Corollary 6.1: Let  $\phi_n: T \rightarrow 2^X$   $(n=1, 2, \dots)$  be a sequence of correspondences satisfying all the assumptions of Theorems 6.4 and 6.5. Suppose that

$$(i) \quad \phi_n(t) \xrightarrow{K-M} \phi(t) \mu\text{-a.e.}$$

Then,

$$\int \phi_n \xrightarrow{K-M} c \int \phi.$$

Moreover, if  $\phi(\cdot)$  is convex valued, then

$$\int \phi_n \xrightarrow{K-M} \int \phi.$$

It should be noted that Theorems 6.1, 6.3 and 6.5 have been established using stronger assumptions than those adopted by Aumann (1965). However, the following example below will show that Aumann's results are false in infinite-dimensional spaces. In particular, without assumption (i) of Theorems 6.1, 6.3 and 6.5, all these results become false.

Example 6.1: Let  $X$  in Theorem 6.1 be equal to  $\ell_2$ , i.e., the space of real sequences  $(a_n)$  for which the norm  $\|a_n\| = (\sum |a_n|^2)^{1/2}$  is finite, and let  $T = [0, 2\pi]$ ,  $\tau$  the Borel sets in  $[0, 2\pi]$  and  $\mu$  the Lebesgue measure on  $(T, \tau)$ . Let  $K = \{x \in \ell_2 : \|x\| \leq 4\pi\}$ . Since the space  $X = \ell_2$  is reflexive the weak and weak\* topologies coincide and thus by the Alaoglu theorem we can conclude that  $K$  is weakly compact. Choose a complete orthogonal system  $\{w_n : n = 0, 1, \dots\}$  in  $L_2(\mu)$  such that each  $w_n$  assumes only the values  $\pm 1$ ,  $w_0 = \chi_{[0, 2\pi]}$  and  $\int_{t \in [0, 2\pi]} w_n(t) d\mu(t) = 0$  for  $n = 1, 2, \dots$ . For each  $n$  and each  $E \in \tau$  let

$$\lambda_n(E) = 2^{-n} \int_{t \in E} \left( \frac{1 + w_n(t)}{2} \right) d\mu(t).$$



Define the vector measure  $V: \tau \rightarrow \ell_2$  by

$$V(E) = (\lambda_0(E), \lambda_1(E), \dots).$$

Then  $\|V(E)\| < 2\mu(E)$  for each  $E \in \tau$ . Therefore, the vector measure  $V$  is countably additive,  $V$  is of bounded variation and it is obviously atomless. Clearly,  $0$  and  $V(T)$  are in  $V(\tau) = \{x \in \ell_2 : x = V(E), E \in \tau\}$  and note that  $\frac{1}{2}V(T)$  is the convex hull of  $V(\tau)$ . The argument now of Lyapunov adopted by Diestel-Uhl (1977, p. 262) can be used here to prove that there is no  $E \in \tau$  such that  $V(E) = \frac{1}{2}V(T)$ , i.e., the  $\ell_2$ -valued atomless vector measure  $V$  of bounded variation is nonconvex.

Observe now that  $\ell_2$  has the RNP. Hence, there exists a function  $g \in L_1(\mu, \ell_2)$  such that for each  $E \in \tau$ ,  $V(E) = \int_{t \in T} \chi_E(t)g(t)d\mu(t)$ . Since the norm closure of the range of  $V$  is convex [Theorem 10, p. 266 in Diestel-Uhl (1977)] we can conclude that  $\frac{1}{2}V(T)$  is in the closure. Consequently, there exists a sequence  $\{E_n : n = 1, 2, \dots\}$  in  $\tau$  such that  $\lim_{n \rightarrow \infty} V(E_n) = \frac{1}{2}V(T)$ . For each  $n$ , define  $\phi_n : T \rightarrow \ell_2$  by  $\phi_n(t) = \chi_{E_n}(t)g(t)$ . It can be easily checked that  $w\text{-}Ls\phi_n$  is measurable [see for instance Yannelis (1989b), Lemma 3.12 and Remark 3.1]. We now show that the inclusion  $w\text{-}Ls \int \phi_n \subset \int w\text{-}Ls\phi_n$  does not hold. In particular, since  $s\text{-}Ls \int \phi_n \subset w\text{-}Ls \int \phi_n$  we will prove a slightly stronger result, i.e., the inclusion  $s\text{-}Ls \int \phi_n \subset w\text{-}Ls \int \phi_n$  does not hold. Note that for each  $n$ ,  $\phi_n(t) \in \{0, g(t)\}$   $\mu$ -a.e. and so  $w\text{-}Ls\phi_n \subset \{0, g(t), \{0, g(t)\}, \emptyset\}$ . For any  $\phi \in S_{w\text{-}Ls\phi_n}^1$  we have that  $\phi(t) = \chi_E(t)g(t)$   $\mu$ -a.e., for  $E \in \tau$ . In order now for the inclusion  $s\text{-}Ls \int \phi_n \subset \int w\text{-}Ls\phi_n$  to hold, we must have that  $\frac{1}{2}V(T) \in \int w\text{-}Ls\phi_n$ , i.e.,  $\frac{1}{2}V(T) = \int_{t \in E} g(t)d\mu(t) = V(E)$ . But as it was remarked above no such

$\varepsilon \tau$  exists (since the vector measure  $V$  is not convex). Hence, the  $w$ - $L_s$  version of the Fatou Lemma fails in infinite-dimensional spaces. Note that the above example also showed that the integral of the closed valued correspondence  $F:T \rightarrow 2^{\ell_2}$  defined by  $F(t) = \{0, g(t)\}$  is not compact (in fact it is not even closed!).<sup>3</sup> Finally, note that  $\frac{1}{2} V(T) = \frac{1}{2} \int_{t \in T} g(t) d\mu(t) \in \text{con } \int F$  and  $\frac{1}{2} V(T) \notin \int F$ , i.e., the integral of the correspondence  $F:T \rightarrow 2^{\ell_2}$  is not convex.<sup>4</sup>

The results below follows directly from Theorems 5.4, 5.6 and Corollary 5.2.

Theorem 6.6: Let  $(T, \tau, \mu)$  be a complete, finite measure space,  $P$  be a metric space and  $X$  be a separable Banach space. Let  $\psi : T \times P \rightarrow 2^X$  be a nonempty valued, integrably bounded correspondence, such that for each fixed  $t \in T$ ,  $\psi(t, \cdot)$  is q.u.s.c. and for each fixed  $p \in P$ ,  $\psi(\cdot, p)$  has a measurable graph. Then

$$\int \psi(t, \cdot) \text{ is q.u.s.c.}$$

Theorem 6.7: Let  $(T, \tau, \mu)$  be a complete, finite measure space,  $X$  be a separable Banach space and  $P$  be a metric space. Let  $\phi : T \times P \rightarrow 2^X$  be an integrably bounded correspondence such that for each fixed  $t \in T$ ,  $\phi(t, \cdot)$  is l.s.c. and for each fixed  $p \in P$ ,  $\phi(\cdot, p)$  has a measurable graph. Then

$$\int \phi(t, \cdot) \text{ is l.s.c.}$$

Remark 6.1: If in addition to the assumptions of Theorem 6.7, it is assumed that  $\int \psi(t, \cdot)$  is compact valued, then we can conclude that  $\int \psi(t, \cdot)$  is u.s.c.

Corollary 6.2: Let  $(T, \tau, \mu)$  be a complete, finite measure space,  $P$  be a metric space and  $X$  be a separable Banach space. Let  $\psi : T \times P \rightarrow 2^X$  be an integrably bounded, nonempty valued correspondence such that for each fixed  $p \in P$ ,  $\psi(\cdot, p)$  has a measurable graph and for each fixed  $t \in T$ ,  $\psi(t, \cdot)$  is continuous. Moreover, suppose that  $\int_T \psi(t, \cdot) d\mu(t)$  is compact valued. Then

$$\int_T \psi(t, \cdot) d\mu(t) \text{ is continuous.}$$

Below we prove a s-Ls version of the Fatou Lemma in infinite dimensions.

Theorem 6.8: Let  $(T, \tau, \mu)$  be a complete, finite measure space and  $X$  be a separable Banach space. Let  $\phi_n : T \rightarrow 2^X$ ,  $(n=1, 2, \dots)$  be a sequence of nonempty valued, graph measurable and integrably bounded correspondences, taking values in a compact, nonempty subset of  $X$ .

Then

$$s\text{-Ls} \int_T \phi_n(t) d\mu(t) \subset \text{cl} \int_T s\text{-Ls} \phi_n(t) d\mu(t).$$

Moreover, if  $\text{Ls} \phi_n(\cdot)$  is convex valued, then

$$s\text{-Ls} \int_T \phi_n(t) d\mu(t) \subset \int_T s\text{-Ls} \phi_n(t) d\mu(t).$$

Proof: Denote by  $P$  the interval  $[0, 1)$ . Define the correspondence  $\psi : T \times P \rightarrow 2^X$  by

$$\psi(t, p) = \begin{cases} \phi_n(t) & \text{if } \frac{1}{n+1} < p < \frac{1}{n} \\ \phi_n(t) \cup \phi_{n+1}(t) & \text{if } p = \frac{1}{n+1} \\ \text{Ls} \phi_n(t) & \text{if } p = 0. \end{cases}$$

It can be easily checked that for each fixed  $t \in T$ ,  $\psi(t, \cdot)$  is u.s.c. and that for each fixed  $p \in P$ ,  $\psi(\cdot, p)$  has a measurable graph. Moreover,  $\psi$  is integrably bounded. Hence,  $\psi$  satisfies all the assumptions of Theorem 6.6 and thus,  $\int_T \psi(t, \cdot) d\mu(t)$  is q.u.s.c. Let now

$x \in \text{Ls} \int_T \phi_n(t) d\mu(t)$ , i.e., there exists  $x_{n_k}$  such that  $\lim_{k \rightarrow \infty} x_{n_k} = x$ ,  $x_{n_k} \in \int_T \phi_{n_k}(t) d\mu(t)$ , ( $k=1, 2, \dots$ ). We wish to show that

$$x \in \text{cl} \int_T \phi_n(t) d\mu(t).$$

Since  $\int_T \psi(t, \cdot) d\mu(t)$  is q.u.s.c. (see Section 2 for a definition) it follows that if  $p_{n_k}$  converges to 0 then  $\int_T \psi(t, p_{n_k}) d\mu(t) \subset \int_T \psi(t, 0) d\mu(t) + \nu B$  for all sufficiently large  $k$  (where  $\nu$  is a small positive number and  $B$  denotes the open unit ball in  $X$ ). Consequently,  $x_{n_k} \in \int_T \psi(t, 0) d\mu(t) + \nu B$  for all sufficiently large  $k$  and therefore,  $x \in \text{cl} \int_T \psi(t, 0) d\mu(t) \equiv \text{cl} \int_T s\text{-Ls} \phi_n(t) d\mu(t)$  as was to be shown. If now  $\text{Ls} \phi_n(\cdot)$ , is convex valued (recall that  $s\text{-Ls} \phi_n(\cdot)$  is closed valued as well) it follows from Theorem 6.1 and the first conclusion of Theorem 6.8 that

$$s\text{-Ls} \int_T \phi_n d\mu(t) \subset \text{cl} \int_T s\text{-Ls} \phi_n(t) d\mu(t) = \int_T s\text{-Ls} \phi_n(t) d\mu(t).$$

This completes the proof of the Theorem.

We close this section by obtaining the following dominated converge result:

Theorem 6.9: Let  $(T, \tau, \mu)$  be a complete, finite measure space and  $X$  be a separable Banach space. Let  $\phi_n : T \rightarrow 2^X$ , ( $n = 1, 2, \dots$ ) be a sequence of integrably bounded, nonempty valued correspondence having a measurable graph, such that

(i) For all  $n$ , ( $n = 1, 2, \dots$ ),  $\phi_n(t) \in K$   $\mu$ -a.e., where  $K$  is a compact, nonempty subset of  $X$ , and

(ii)  $\phi_n(t) \rightarrow \phi(t)$   $\mu$ -a.e.

Then

$$\int_T \phi_n(t) d\mu(t) \rightarrow c\ell \int_T \phi(t) d\mu(t).$$

Moreover, if  $\phi(\cdot)$  is convex valued then

$$\int_T \phi_n(t) d\mu(t) \rightarrow \int_T \phi(t) d\mu(t).$$

Proof: Since by assumption  $\phi_n(t) \rightarrow \phi(t)$   $\mu$ -a.e., i.e.,  $\phi(t) = s\text{-Li} \phi_n(t) = s\text{-Ls} \phi_n(t)$   $\mu$ -a.e., it follows from Theorems 6.4 and 6.8 that:

$$(6.1) \quad \int \phi = \int s\text{-Li} \phi_n \in s\text{-Li} \int \phi_n \in s\text{-Ls} \int \phi_n \in c\ell \int s\text{-Ls} \phi_n = c\ell \int \phi.$$

Therefore,

$$c\ell \int_T \phi(t) d\mu(t) = s\text{-Li} \int_T \phi_n(t) d\mu(t) = s\text{-Ls} \int_T \phi_n(t) d\mu(t),$$

i.e.,

$$\int_T \phi_n(t) d\mu(t) \rightarrow c\ell \int_T \phi(t) d\mu(t).$$

If now  $\phi(\cdot)$  is convex valued, (6.1) can be written (recall the second conclusion of Theorem 6.8) as:

$$\int \phi = \int s\text{-Li} \phi_n \in s\text{-Li} \int \phi_n \in s\text{-Ls} \int \phi_n \in \int s\text{-Ls} \phi_n = \int \phi.$$

Thus,

$$\int_T \phi(t) d\mu(t) = s\text{-Li} \int_T \phi_n(t) d\mu(t) = s\text{-Ls} \int_T \phi_n(t) d\mu(t),$$

i.e.,

$$\int_T \phi_n(t) d\mu(t) \rightarrow \int_T \phi(t) d\mu(t),$$

and this completes the proof of Theorem 6.9.

Footnotes: <sup>1</sup>Note that the assumption that  $X$  has the RNP is not needed for proving that the norm closure of the vector measure  $V$  is convex.

<sup>2</sup>Alternatively, Corollary 6.1 follows directly from Corollary 5.1.

<sup>3</sup>Recall that Aumann (1965) demonstrated that if  $X$  is finite dimensional and  $F : T \rightarrow 2^X$  is integrably bounded and closed valued, then  $\int F$  is compact.

<sup>4</sup>Note that when  $X$  is finite dimensional the well-known result of Richter (1963) assures that  $\int F$  is convex.

Bibliographical Notes: A version of Theorem 6.1 is proved by Yannelis (1988). Theorem 6.2 is due to Datko (1973). The proof given here is taken from Khan (1985). It should be noted that Theorem 6.2 is the infinite dimensional version of a well-known result of Richter (1963). Theorem 6.3 is an infinite dimensional version of Theorem 2 of Aumann (1965) [see also Debreu (1967)] and it was first proved by Datko (1973) for  $X$  being a reflexive separable Banach space. The reflexivity assumption was subsequently relaxed by Khan (1985). Rustichini-Yannelis (1988) showed that if the dimensionality of the measure space

is bigger than the dimensionality of the space  $X$ , then the conclusion of Theorem 6.3 can be strengthened to  $\sqrt{\text{con}\phi} = \int\phi$ .

The Example 6.1 is due to Lyapunov [see also Diestel-Uhl (1977, p. 262)]. The argument used to prove that several of the properties of the Aumann integral fail in an infinite dimensional setting is due to Rustichini (1989). Theorems 6.6-6.9 are due to Yannelis (1988a). Related results to Theorems 6.6-6.9 were obtained by Debreu (1967).

### 7. THE GEL'FAND INTEGRAL

Let  $(T, \tau, \mu)$  be a finite measure space and  $X$  be a Banach space. Let  $f : T \rightarrow X^*$  be a function such that  $\langle f, x \rangle \in L_1(\mu)$  for all  $x \in X$ , then for each  $A \in \tau$  the element  $x_A^*$  in  $X^*$  is called the Gel'fand integral of  $f$  over  $A$ , where

$$x_A^*(x) = \int_A \langle f(t), x \rangle d\mu(t) \text{ for all } x \in X.$$

We denote by  $(S_\phi^1)^*$  the set of all Gel'fand integral selections from the correspondence  $\phi : T \rightarrow 2^{X^*}$ , i.e.,

$$\begin{aligned} (S_\phi^1)^* &= \{x \in (L_1(\mu, X))^* : x(t) \in \phi(t) \mu\text{-a.e.}\} \\ &= \{x \in L_\infty(\mu, X^*) : x(t) \in \phi(t) \mu\text{-a.e.}\}. \end{aligned}$$

The Gel'fand integral of the correspondnece  $\phi : T \rightarrow 2^{X^*}$  is defined as follows:

$$\int \phi(t) d\mu(t) = \{ \int \langle f(t), x \rangle d\mu(t) : f \in (S_\phi^1)^* \text{ for all } x \in X \}.$$

Note that the above integral may be empty unless  $\phi$  admits weak\* measurable selections. A very useful result due to Khan (1985) which

has found several applications in game theory and general equilibrium is the fact that the weak\* closure of the Gel'fand integral of a correspondence is convex. This result can be proved adopting a similar argument used to prove Theorem 6.2 except that instead of using Uhl's Theorem one can now appeal to a result of Kluvarek [Kluvarek (1973, p. 46, Lemma 5)]. We state below a very useful result for the Gel'fand integral of a correspondence.

Theorem 7.1: Let  $(T, \tau, \mu)$  be a complete finite measure space,  $X^*$  be the dual of a separable Banach space and  $\phi : T \rightarrow 2^{X^*}$  be a correspondence with a weak\* measurable graph (i.e.,  $G_\phi \in \tau \otimes \beta_{w^*}(X)$ , where  $\beta_{w^*}(X)$  are the Borel subsets of  $X^*$  in the weak\* topology of  $X^*$ ) such that  $\phi(t)$  is weak\* closed and bounded for almost all  $t$  in  $T$ . Then for all  $A \in \tau$ ,

$$w^* - \text{cl} \int_A \phi = \int_A \overline{w^* - \text{con} \phi}.$$

Moreover,  $\int_A \overline{w^* - \text{con} \phi}$  is weak\* compact and convex.

Bibliographical Notes: Theorem 7.1 is due to Khan (1985) and it has found important applications in general equilibrium theory [Rustichini-Yannelis (1987), Ostroy-Zame (1988)], game theory [Cotter (1988), Khan (1986)] and demand theory [Border (1987)].



## 8. APPLICATIONS

In this section we will indicate how some of the results in Yannelis (1989b) as well as theorems of this paper can be used to prove the existence of an equilibrium in an abstract economy with a measure space of agents.

An abstract economy  $\Gamma$  is a quadruple  $[(T, \tau, \mu), X, P, A]$ , where

- (1)  $(T, \tau, \mu)$  is the measure space of agents,
- (2)  $X : T \rightarrow 2^Y$  is the strategy correspondence (where  $Y$  is a linear topological space),
- (3)  $P : T \times S_X^1 \rightarrow 2^Y$  is a preference correspondence such that  $P(t, x) \subset X(t)$  for all  $(t, x) \in T \times S_X^1$ , and
- (4)  $A : T \times S_X^1 \rightarrow 2^Y$  is a constraint correspondence such that  $A(t, x) \subset X(t)$  for all  $(t, x) \in T \times S_X^1$ .

The interpretation of the preference correspondence  $P : T \times S_X^1 \rightarrow 2^Y$  is as follows: We read  $y \in P(t, x)$  as "agent  $t$  strictly prefers  $y$  to  $x(t)$  if the given strategies of other agents are fixed." Throughout this section we set  $Y = \mathbb{R}^n$  and endow  $S_X^1$  with the weak topology.

An equilibrium for  $\Gamma$  is an  $x^* \in S_X^1$  such that for almost all  $t$  in  $T$  the following conditions hold:

- (i)  $x^*(t) \in A(t, x^*)$
- (ii)  $P(t, x^*) \cap A(t, x^*) = \emptyset$ .

Below we state the assumptions needed for the proof of our equilibrium existence theorem.

- (8.1)  $(T, \tau, \mu)$  is a complete finite separable measure space.

(8.2)  $X : T \rightarrow 2^{\mathbb{R}^n}$  is a correspondence such that:

(a) It is integrably bounded and for all  $t \in T$ ,  $X(t)$  is a closed convex nonempty subset of  $\mathbb{R}^n$ ;

(b)  $X(\cdot)$  is lower measurable.

(8.3)  $A : T \times S_X^1 \rightarrow 2^{\mathbb{R}^n}$  is a correspondence such that:

(a) for each fixed  $t \in T$ ,  $A(t, \cdot)$  is continuous;

(b)  $A(\cdot, \cdot)$  is closed, convex and nonempty valued;

(c) for each fixed  $x \in S_X^1$ ,  $A(\cdot, x)$  is lower measurable.

(8.4)  $P : T \times S_X^1 \rightarrow 2^{\mathbb{R}^n}$  is a correspondence such that:

(a) for each fixed  $t \in T$ ,  $P(t, \cdot)$  has an open graph in  $S_X^1 \times \mathbb{R}^n$ ;

(b)  $x(t) \notin \text{con}P(t, x)$  for all  $x \in S_X^1$ ,  $\mu$ -a.e.;

(c) for every open subset  $V$  of  $\mathbb{R}^n$ , the set

$\{(t, x) \in T \times S_X^1 : A(t, x) \cap \text{con}P(t, x) \cap V \neq \emptyset\}$  belongs to  $\tau \otimes \beta_w(S_X^1)$ , where  $\beta_w(S_X^1)$  denotes the Borel  $\sigma$ -algebra for the weak topology on  $S_X^1$ .

We are now ready to state the following result:

Theorem 8.1: Let  $\Gamma = [(T, \tau, \mu), X, P, A]$  be an abstract economy satisfying (8.1)-(8.4). Then an equilibrium in  $\Gamma$  exists.

Proof: Define the set-valued function  $\psi : T \times S_X^1 \rightarrow 2^{\mathbb{R}^n}$  by  $\psi(t, x) = \text{con}P(t, x)$ . It can be easily checked that for each fixed  $t \in T$ ,  $\psi(t, \cdot)$  has an open graph in  $S_X^1 \times \mathbb{R}^n$  [see for instance Lemma 4.1 in Yannelis (1987)]. Define the set-valued function  $\phi : T \times S_X^1 \rightarrow 2^{\mathbb{R}^n}$

by  $\phi(t,x) = \psi(t,x) \cap A(t,x)$ . It follows from Lemma 4.2 in Yannelis (1987) that for each fixed  $t \in T$ ,  $\phi(t,\cdot)$  is weakly l.s.c., i.e., for every open subset  $V$  of  $\mathbb{R}^n$ , the set  $\{x \in S_X^1 : \phi(t,x) \cap V \neq \emptyset\}$  is weakly open in  $S_X^1$ . By assumption (8.4)(c),  $\phi(\cdot,\cdot)$  is lower measurable. Let  $U = \{(t,x) \in T \times S_X^1 : \phi(t,x) \neq \emptyset\}$ . By Theorem 4.2 in Yannelis (1989b) we can guarantee the existence of a Carathéodory-type selection, i.e., there exists a function  $f : U \rightarrow \mathbb{R}^n$  such that  $f(t,x) \in \phi(t,x)$  for all  $(t,x) \in U$  and for each  $t \in T$ ,  $f(t,\cdot)$  is continuous on  $U_t = \{x \in S_X^1 : \phi(t,x) \neq \emptyset\}$  and for each  $x \in S_X^1$ ,  $f(\cdot,x)$  is measurable on  $U_x = \{t \in T : \phi(t,x) \neq \emptyset\}$ . Moreover,  $f(\cdot,\cdot)$  is jointly measurable. Define the set-valued function  $F : T \times S_X^1 \rightarrow 2^{\mathbb{R}^n}$  by

$$F(t,x) = \begin{cases} \{f(t,x)\} & \text{if } (t,x) \in U \\ A(t,x) & \text{if } (t,x) \notin U. \end{cases}$$

It follows at once from the l.s.c. of  $\phi(t,\cdot)$  that for each  $t \in T$  the set  $U_t = \{x \in S_X^1 : \phi(t,x) \neq \emptyset\}$  is weakly open in  $S_X^1$ . Thus, by Lemma 6.1 in Yannelis-Prabhakar (1983) for each fixed  $t \in T$ ,  $F(t,\cdot)$  is weakly u.s.c. in the sense that the set  $\{x \in S_X^1 : F(t,x) \subset V\}$  is weakly open in  $S_X^1$  for every open subset  $V$  of  $\mathbb{R}^n$ . As in Yannelis (1987) one can easily check that for each  $x \in S_X^1$ ,  $F(\cdot,x)$  has a measurable graph. Also,  $F(\cdot,\cdot)$  is closed, convex and nonempty valued.

Define the set-valued function  $\theta : S_X^1 \rightarrow 2^{S_X^1}$  by

$$\theta(x) = \{y \in S_X^1 : y(t) \in F(t,x) \text{ } \mu\text{-a.e.}\}.$$

Note that by Theorem 3.1,  $S_X^1$  is weakly compact in  $L_1(\mu, \mathbb{R}^n)$ . Since the measure space  $(T, \tau, \mu)$  is separable,  $L_1(\mu, \mathbb{R}^n)$  is a separable Banach space. Since, weakly compact subsets of a separable Banach space are metrizable, we can conclude that  $S_X^1$  is metrizable. Hence, it follows from Theorem 5.5 that  $\theta(\cdot)$  is weakly u.s.c, i.e., for every weakly open subset  $V$  of  $S_X^1$  the set  $\{x \in S_X^1 : \theta(x) \subset V\}$  is weakly open in  $S_X^1$ . Appealing to the Aumann measurable selection theorem, we can conclude that  $\theta(\cdot)$  is nonempty valued. Similarly, the set  $S_X^1$  is nonempty. Obviously  $\theta(\cdot)$  is convex valued and so is the set  $S_X^1$ . It follows from the Fan-Glicksberg fixed point theorem that there exists  $x^* \in S_X^1$  such that  $x^* \in F(x^*)$ . It can be easily now checked that the fixed point is by construction an equilibrium for the abstract economy  $\Gamma$ .

Bibliographical Notes: This section is based on Yannelis (1987) where we refer the reader for related results. However, we must point out that the notion of an equilibrium for an abstract economy is due to Debreu (1952) which in turn generalizes the notion of a noncooperative equilibrium for a game in normal form introduced by Nash (1951). For more applications of Carathéodory-type selections theorems as well as recent results on integration of set-valued functions we recommend, the papers of Kim-Prikry-Yannelis (1989), Yannelis-Rustichini (1988) and Balder-Yannelis (1988). Finally a paper by Debreu (1967) uses measure theory and measurable selections extensively.

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