# Variational Bewley Preferences

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#### Abstract

This paper characterize preference relations over Anscombe and Aumann acts and give necessary and sufficient conditions that guarantee the existence of a utility function u on consequences and an *ambiguity index*  $\eta$  on the set of probabilities on the states of the nature such that, for all acts f and g,

$$f \succsim g \Leftrightarrow \int u(f)dp + \eta(p) \geq \int u(g)dp, \, \forall p \in \Delta.$$

The function u represents the decision maker's risk attitudes, while the ambiguity index  $\eta(p)$  about the prior p captures its relative subjective degree of plausibility. The axiomatic basis for this class of preference waiver completeness and transitivity, and an interesting property is that cycles are avoided. These preferences include the Knightian decision theory of Bewley as well new class of preferences through specifics ambiguity index.

Another contribution in this paper starts from a pair of preferences and provides a novel foundation for variational preferences of Macheroni, Marinacci and Rustichini, based on axioms on these relations that allow a joint representation by a single ambiguity index.

KEYWORDS: Ambiguity, Knightian uncertainty, variational representations.

## 1 Introduction

In the 80s two alternatives axiomatic approaches appeared as foundations for the distinction proposed by Frank Knight (1921) between risk and uncertainty.

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Bearing in mind that risk is characterized by randomness with well defined probabilities and uncertainty captures randomness with vague probabilities, both Gilboa and Schmeidler (1989) and Bewley (2002) proposed a set of axioms for preference relations on uncertainty acts endogenously getting a set of probabilities compatible with the decision maker's beliefs, which led to *multiple priors* models. On the other hand, previously theoretical developments as the famous axiomatizations of subjective expected utility theory (SEU), as proposed by Savage (1954) and Anscombe and Aumann (1963), had suggest that the Knight's distinction is irrelevant because any uncertainty can be modeled through probabilities, in fact, in such theory decision makers aims at maximizing his expected utility with respect to some subjective probabilities.

Multiple priors models were inspired also by the well known objection to the theory of subjective probability formulated by Ellsberg (1961), which formed the basis for the notion of *ambiguity*: an event is ambiguous if it has a unknown probability. In fact, Ellsberg showed that individuals may prefer gambles with precise probability to gambles with unknown odds, that is, ambiguity matters for choice<sup>1</sup>. In this way, ambiguity has been a classic issue in decision theory and its main contribution is to provide rigorous foundations for situations where there may be no probability on the states of the nature that the decision maker holds and that rationalizes his choices, or else situations where the lack of well comparisons for some pair of uncertainty alternatives are not avoided.

As regards the axiomatic foundation, while the maxmin expected utility model (MEU) of Gilboa and Schmeidler (1989) is based in a weaker version of independence axiom as presented in the Anscombe and Aumann's list of axiom, the theory proposed by Bewley (2002) for Knightian uncertainty or ambiguity presents as main behavioral feature the lack of completeness in the decision maker's preference relation<sup>2</sup>. In the Bewley's model a set of priors C determines a preference relation via an unanimity rule: an act f is strictly better than an act g if and only if the expected utility of f is strictly higher than the expected utility of g for every prior p in the set C.

Ghirardato, Maccheroni, Marinacci and Siniscalchi (GMMS, 2003) provide a derivation of Bewley's model in the purely subjective probability framework a la Savage, but such derivation differs from Bewley's on some aspects, most important is that Bewley considers as primitive a strict preference relation while GMMS propose a representation using a reflexive relation as primitive which delivers an unanimity rule where f is at least as desirable as g if and only if the expected utility of f is at least as high as the expected utility of g for every prior p in the set  $C^3$ .

<sup>&</sup>lt;sup>1</sup>Although many arguments showed the that people often fail to behave in accordance with the subjective expected utility, Savage and Anscombe-Aumann provided as a legacy an important framework that serves as the basis for much of the recent developments in the theory of decision under ambiguity.

<sup>&</sup>lt;sup>2</sup>Recently, Nascimento and Riella (2008) unified both approaches through an axiomatic foundation for a class of incomplete and ambiguity averse preferences in the sense of Ghirardato and Marinacci (2002).

<sup>&</sup>lt;sup>3</sup>Ghirardato, Maccheroni and Marrinaci (GMM, 2004) obtained the same result in the Anscombe and Aumann's set up for general state space. See also Giroto and Holzer (2005).

The main idea of Bewley's model is that the presence of uncertainty might make the agent confused, which induces he stay with her status quo. In fact, the ambiguity aversion may reduces her confidence in her ability to compare some alternatives, as consequence, we observe the incompleteness of the preference relation as explained above. An important point is the inertia assumption proposed by Bewley: we view the agent in question as considering a set of priors beliefs in her decision on whether to abandon the status quo, and some degree of dominance using this set of priors is requiring before moving away from her status quo.

However, a natural point is that decision makers might has a non uniform feeling of plausibility among the class of reasonable models<sup>4</sup>, and such factor should rule out the original Bewley's unanimity principle because it implicitly requires an uniform degree of importance among plausible priors. Intuitively, assuming a decision maker with a non uniform degree of confidence among priors, it seems more appeal a decision criteria under which a relative dominance rule imposes that non full plausibility are related to some amount of acceptable loss in terms of expected utility. Bewley's model is too extreme in the sense that a plausible priors are given by only probabilities in the set C and every plausible prior has an identical degree of confidence.

Aiming to get a model that captures the previous considerations, we characterized preference relations on the set of Anscombe and Aumann's acts where a relative dominance rule is obtained. Our axiomatization generates a decision rule that generalizes the model proposed by Bewley (2002) via the notion of ambiguity index (or level): the decision maker's subjective ambiguity index is a special mapping  $\eta$  over the set of all probability measures  $\Delta$  with values in  $\mathbb{R}_+ \cup \{+\infty\}$  and the preference relation  $\succeq$  satisfies,

$$f \succeq g \Leftrightarrow \int u(f)dp + \eta(p) \ge \int u(g)dp, \, \forall p \in \Delta.$$

Where, u is the von Neumann-Morgenstern utility function over the set of lotteries X. Note that if  $\eta(\cdot) = \delta_C(\cdot)$  for some (convex and closed) set of probability measures then we obtain the Bewley's decision rule. We axiomatize preferences, called *variational Bewley preferences*, consistent with the decision rule above by showing how it rests on a simple set of axioms that generalizes the Bewley's model as studied by Ghirardato, Maccheroni and Marinacci (2004), being more precisely, we do not impose transitivity and we use a weaker condition than the independence axiom.

In fact, beyond a condition weaker than independence, in this paper both completeness as transitivity are not imposed for a preference relation. It is consistent with Aumann (1962) complains about the inaccurate description of actual behavior implied by completeness axiom and the normative viewpoint demanding that decision makers should make well comparison of every pair

<sup>&</sup>lt;sup>4</sup>Following the MEU tradition dropping the classical independence axiom, some works capture a similar idea, e.g., Maccheroni, Marinacci and Rustichini (2006) and Chateauenuf and Faro (2009).

of alternatives. Mandler (2005) extended this criticism to incomplete and intransitive preferences by showing that even decision makers with such kind of preferences are not necessarily subject to money-pumps. Interestingly, we show that even intransitive any variational Bewley preference is acyclic.

We obtain also an interesting relationship between variational Bewley preference and variational preferences introduced by Maccheroni, Marinacci and Rustichini (MMR, 2006). In fact, in the same way as obtained by Gilboa, Maccheroni, Marinacci and Schmeidler (GMMS, 2008) in their paper about multiple prior model, we show that taking two preference relations  $\succeq^*$  and  $\succeq^{**}$  that jointly satisfy Consistency and Default to Certainty, as introduced by GMMS (2008), where  $\succeq^*$  is a variational Bewley preferences represented by a pair  $(u, \eta)$  and  $\succeq^{**}$ is a complete continuous preorder, then  $\succeq^{**}$  should be a variational preference represented by  $(u, \eta)$ . So, this result can be viewed as proving a novel foundation for variational preferences, based on the interplay of the two preferences  $\succeq^*$  and  $\succeq^{**}$ . Note that variational representation of preferences can be derived without assuming the Uncertainty Aversion axiom of Gilboa and Schmeidler (1989) and without the Weak Certainty Independence axiom of MMR (2006).

The paper is organized as follows. After introducing the setup in Section 2 and the set of axioms in Section 3, we present the main representation result in Section 4. In Subsection 4.1 we derive conditions in order to obtain the countable additive case and in the Subsection 4.2 we discuss the ambiguity revealing properties, in the sense of Ghirardato, Maccheroni and Marinacci (2004), featured by the class of preferences characterized in the main result. In Section 5, we study the interplay of preferences characterized in our main result with the class of variational preferences. In Section 6, we study some special cases, namely the incomplete preferences of Bewley (1989) as well its special case given by the SEU model of Anscombe and Aumann (1963). Also, we derive some special class of variational Bewley preferences, *e.g.*, the intransitive and incomplete entropic preferences obtained through the relative entropic ambiguity index. Proofs and related material are collected in the Appendix.

## 2 Framework

Consider a set S of states of nature (world), endowed with an  $\sigma$ -algebra  $\Sigma$  of subsets called *events*, and a non-empty set X of consequences. We denote by  $\mathcal{F}$  the set of all the (simple) acts: finite-valued functions  $f: S \to X$  which are  $\Sigma$ -measurable<sup>5</sup>. Moreover, we denote by  $B_0(\Sigma)$  the set of all simple real-valued  $\Sigma$ -measurable functions  $a: S \to \mathbb{R}$ . The norm in  $B_0(\Sigma)$  is given by  $\|a\|_{\infty} = \sup_{s \in S} |a(s)|$  (called *sup norm*) and will denote by  $B(\Sigma)$  the supnorm closure of  $B_0(\Sigma)$ .

Given a mapping  $u : X \to \mathbb{R}$ , the function  $u(f) : S \to \mathbb{R}$  is defined by u(f)(s) = u(f(s)), for all  $s \in S$ . We note that  $u(f) \in B_0(S, \Sigma)$  whenever f belongs to  $\mathcal{F}$ .

<sup>&</sup>lt;sup>5</sup>Let  $\succeq_0$  be a binary relation on X, we say that a function  $f: S \to X$  is  $\Sigma$ -measurable if, for all  $x \in X$ , the sets  $\{s \in S : f(s) \succeq_0 x\}$  and  $\{s \in S : f(s) \succ_0 x\}$  belong to  $\Sigma$ .

Let x belong to X, define  $x \in \mathcal{F}$  to be the constant act such that x(s) = x for all  $s \in S$ . Hence, we can identify X with the set  $\mathcal{F}_c$  of the constant acts in  $\mathcal{F}$ .

Additionally, we assume that the set of consequences X is a convex subset of a vector space. For instance, this is the case if X is the set of all simple lotteries on a set of *outcomes* Z. In fact, it is the classic setting of Anscombe and Aumann (1963) as re-started by Fisburn (1970).

Using the linear structure of X we can define as usual for every  $f, g \in \mathcal{F}$  and  $\alpha \in [0, 1]$  the act:

$$\begin{aligned} \alpha f + (1 - \alpha)g &: S \to X \\ (\alpha f + (1 - \alpha)g)(s) &= \alpha f(s) + (1 - \alpha)g(s) \end{aligned}$$

Also, given two acts  $f, g \in \mathcal{F}$  and an event  $A \in \Sigma$  we denote by fAg the act h such that  $h \mid_A = f$  and  $h \mid_{A^c} = g$ .

We denote by  $\Delta := \Delta(\Sigma)$  the set of all (finitely additive) probability measures  $p: \Sigma \to [0, 1]$  endowed with the natural restriction of the well known weak\* topology  $\sigma(ba, B)$ . We say that a mapping  $\eta: \Delta \to [0, \infty]$  is grounded if  $\{\eta = 0\} := \{p \in \Delta : \eta(p) = 0\} \neq \emptyset$  and its effective domain is defined by  $dom(\eta) := \{\eta < \infty\}$ . Also,  $\eta$  is weak\* lower semicontinuous if  $\{\eta \leq r\}$  is weak\* closed for each  $r \geq 0$ . Moreover, we denote by  $\Delta^{\sigma}$  the set of all countably additive probabilities in  $\Delta$ . In particular, given  $q \in \Delta^{\sigma}$ , we denote by  $\Delta^{\sigma}(q)$  the set of all probabilities in  $\Delta^{\sigma}$  that are absolutely continuous w.r.t. q, *i.e.*,  $\Delta^{\sigma}(q) = \{p \in \Delta^{\sigma} : p \ll q\}$ , where  $p \ll q$  means that  $\forall A \in \Sigma$ , if q(A) = 0 then p(A) = 0.

Functions of the form  $\eta : \Delta \to [0, \infty]$  will play a key role in the paper because it will capture the subjective degree of plausibility of the decision makers. We denote by  $\mathcal{N}(\Delta)$  the class of these functions such that  $\eta$  is grounded, convex and weak<sup>\*</sup> lower semicontinuous.

The decision maker's preferences are given by a binary relation  $\succeq$  on  $\mathcal{F}$ , whose the usual symmetric and asymmetric components are denoted by  $\sim$  and  $\succ$ .

### 3 Axioms

Next we describe the axioms assumed for a preference relation  $\succeq$  on the set of Anscombe and Aumann acts  $\mathcal{F}$ , which characterizes a class of preferences that we dub variational Bewley preferences:

(Axiom 1)  $\succeq$  is reflexive: For any  $f \in \mathcal{F}, f \succeq f$ .

(Axiom 2) The restriction on lotteries  $\gtrsim |_{X \times X}$  is nontrivial, complete and transitive.

(Axiom 3) Archimedean Continuity. For all  $f, g, h \in \mathcal{F}$  the sets:

$$\{\alpha \in [0,1] : \alpha f + (1-\alpha)g \succeq h\} \text{ and } \{\alpha \in [0,1] : h \succeq \alpha f + (1-\alpha)g\} \text{ are closed}$$
  
in [0,1].

(Axiom 4) Monotonicity. For every  $f, g \in \mathcal{F}$ :

if 
$$f(s) \succeq (\succ) g(s)$$
 for any  $s \in S$  then  $f \succeq (\succ) g$ .

(Axiom 5) Dominance Independence: For every  $f, g, h_1, h_2 \in \mathcal{F}$ , and every  $\alpha \in (0, 1)$ ,

if  $f \succeq g$  and  $h_1 \succeq h_2$  then  $\alpha f + (1 - \alpha)h_1 \succeq \alpha g + (1 - \alpha)h_2$ .

( Axiom 6 ) Unboundedness. There are  $x,y\in X$  such that, for each  $\alpha\in(0,1),$  there exist  $z,\widehat{z}\in X$  such that

$$\alpha z + (1 - \alpha) y \succ x \succ y \succ \alpha \hat{z} + (1 - \alpha) x.$$

Since we are following the standard notion of weak preference, *i.e.*, given two acts f and g the relation  $f \succeq g$  means that "f is at least as good as g", Axiom 1 seems very natural because it says that any act is at least as good as the same. On the other hand, we relax the usual completeness and transitivity conditions about preferences over uncertainty acts.

Axiom 2 means that preferences over consequences satisfies standard assumptions concerning the *classical notion of rationality*, and also there is at least one par of consequences for which the decision maker is not indifferent between then. Axiom 3 and Axiom 6 are technical assumptions.

Axiom 4 is a state-independence condition for both weak and strict sense of preference, saying that decision makers always prefer acts delivering state-wise better payoffs, regardless of the state where the better payoffs occur.

Axiom 5 says that if a decision maker has two well defined preference between two pars of acts then for any two acts obtained through mixtures from the two best and worst acts of originals comparisons, respectively, then the preference between new acts obtained should respect the original ordering<sup>6</sup>. We note that Axiom 5 does not implies the usual Independence axiom that says:

Independence: For every  $f, g, h \in \mathcal{F}$ , and every  $\alpha \in (0, 1)$ ,

 $f \succeq g \text{ iff } \alpha f + (1 - \alpha) h \succeq \alpha g + (1 - \alpha) h.$ 

On the other side, Dominance Independence axiom is stronger than the following weaker version of Independence:

W-Independence: For every  $f, g, h \in \mathcal{F}$ , and every  $\alpha \in (0, 1)$ ,

 $f \succeq g$  implies  $\alpha f + (1 - \alpha) h \succeq \alpha g + (1 - \alpha) h$ .

It is worth noting that for variational Bewley preferences, in general, it is not true the converse of W-independence. On the other hand, variational Bewley preferences satisfies the following stronger version of Archimedean Continuity:

S-Continuity: For all  $e, f, g, h \in \mathcal{F}$ , the set

$$\{\alpha \in [0,1] : \alpha f + (1-\alpha) g \succeq \alpha g + (1-\alpha) e\} \text{ is closed in } [0,1].$$

An interesting fact is that a reflexive and *transitive* preference relation that satisfies W-independence and S-continuity should satisfies Independence<sup>7</sup>. As

<sup>&</sup>lt;sup>6</sup>Technically, Axiom 5 says that the preference  $\succeq$  is a convex subset of  $\mathcal{F} \times \mathcal{F}$ .

<sup>&</sup>lt;sup>7</sup>See, for instance, Lemma 1 at page 127 of Dubra, Maccheroni and Ok (2004).

consequence, if we add transitivity to the set of our axioms then we obtain that our preference should satisfies Independence.

Finally, we end this section noting that though we drop transitivity, our set of axioms entails the following reasonable property weaker than transitivity<sup>8</sup>:

Dominance: If  $f \succeq g$  and  $h(s) \succeq f(s)$  for any  $s \in S$  then  $h \succeq g$ .

## 4 Main Representation and Properties

We now derive our general representation that relies on Axioms A1-A6.

**Theorem 1** Let  $\succeq$  be a preference relation on the set of Anscombe-Aumann acts  $\mathcal{F}$ . Then the following conditions are equivalent:

(1)  $\succeq$  satisfies assumptions A.1-A.6.

(2) There exists an affine utility index  $u : X \to \mathbb{R}$ , with  $u(X) = \mathbb{R}$ , and a function  $\eta : \Delta \to [0, \infty]$  that belongs to  $\mathcal{N}(\Delta)$  such that, for all f and g in  $\mathcal{F}$ ,

$$f \succeq g \Leftrightarrow \int u(f)dp + \eta(p) \ge \int u(g)dp, \, \forall p \in \Delta.$$

Moreover, u in (2) is unique up to positive linear transformation and for each u there is a (unique) minimal  $\eta^* : \Delta \to [0, \infty]$  consistent with the decision rule above and it is given by

$$\eta^*(p) = \sup_{(f,g)\in \succeq} \left( \int \left( u(g) - u(f) \right) dp \right), \ \forall p \in \Delta.$$

The representation above involves a mapping  $\eta$  defined on  $\Delta \subset B(\Sigma)^*$  which is a grounded, convex and weak<sup>\*</sup> lower semicontinuous function, hence it can be viewed as a *Fenchel conjugate* of some functional on  $B(\Sigma)$ , which is one of the most classic tool in variational analysis<sup>9</sup>. This motivates the following definition:

**Definition 2** A preference  $\succeq$  on  $\mathcal{F}$  is called variational Bewley preference if it satisfies Axioms A.1–A.6.

Following the Bewley inertia idea, an interesting interpretation for  $\eta$  says that  $\eta(p)$  measure the maximal expected loss accepted by the decision maker if p is true model. Note that  $\eta(p) < \eta(q)$  says that p is subjectively more plausible than q. So, the dominance reflects such difference on the decision maker's confidence among priors:

$$f \succeq g \Leftrightarrow \int (u(f) - u(g))dp \ge -\eta(p), \ \forall p \in \Delta,$$

<sup>&</sup>lt;sup>8</sup>We show this fact in the begin of the proof of the main theorem.

<sup>&</sup>lt;sup>9</sup>See, for instance, Brézis (1984), page 8.

*i.e.*, for priors the most plausible priors (*i.e.*, for priors  $p \in \{\eta = 0\}$ ) we have the dominance *a la* Bewley

$$\int u(f)dp \ge \int u(g)dp, \,\forall p \in \{\eta = 0\}\,,$$

otherwise, the decision maker is willing to accept at most a loss (in terms of expected value) equal to  $-\eta(p)$  for abandon the status quo.

An interesting aspect of our representation rule is concerns about the indifference relation  $\sim$ , in fact, since  $f \sim g$  iff  $f \succeq g$  and  $g \succeq f$ , the main theorem entails that

$$f \sim g \text{ iff } \eta(p) \ge \left| \int u(f) \, dp - \int u(g) \, dp \right|, \forall p \in \Delta.$$

Hence, indifference is equivalent to the fact that, for any prior, the module of the difference between the corresponding expected utilities is limited by the prior's plausibility. So, for priors with full plausibility the difference should be null; on the other hand, by considering priors with small plausibility degree, indifference in preference is consistent with the possibility of a significant difference between the corresponding expected values.

By Theorem 1, variational Bewley preferences can be represented by a pair  $(u, \eta^*)$ . Hence, we will write u and  $\eta^*$  to denote our class of preferences. From now on, when we consider a variational Bewley preference, we will write u and  $\eta$  to denote the elements of such a pair. Next we give the uniqueness properties of this representation.

**Corollary 3** Two pairs  $(u, \eta^*)$  and  $(u_1, \eta_1^*)$  represent the same variational Bewley preference  $\succeq$  if and only if there exists  $\alpha > 0$  and  $\beta \in \mathbb{R}$  such that  $u_1 = \alpha u + \beta$ and  $\eta_1^* = \alpha \eta^*$ .

An interesting consequence of this uniqueness result together with the Bewley's unanimity rule, as characterized by Ghirardato Maccheroni and Marinacci (2004), is that our preference relation, in general, is not transitive. For instance, if we assume that "ambiguity index"  $\eta^*$  is given by the well known relative entropic index then the induced preference is not transitive because  $\alpha \eta^*$ , with  $\alpha > 0$ , is never an indicator function<sup>10</sup>.

Fortunately, variational Bewley preferences are not subject to money-pumps and it is a consequence of next proposition saying that variational Bewley preferences are acyclic.

**Proposition 4** If a preference  $\succeq$  on the set of Anscombe and Aumann act is a variational Bewley preference then the induced asymmetric component  $\succ$  is acyclic. In fact,

$$f \succ g \Rightarrow V(f) > V(g),$$

 $<sup>^{10}</sup>$  For more details see Section 6.

where V is a variational representation of a variational preference (MMR 2006) given by

$$V\left(f
ight)=\min_{p\in\Delta}\left(\int u\left(f
ight)dp+\eta^{*}\left(p
ight)
ight).$$

### 4.1 Countable Additive Priors

In our previous analysis we considered the set  $\Delta$  of all finitely additive probabilities. By its very convenient analytical properties in applications it is very useful to consider the case of countably additive probabilities. As we will see momentarily that this is the case for the construction of some interesting examples.

If we add the transitivity condition in order to recover the Bewley model as in Ghirardato, Maccheroni and Marinacci (2004), we have that the well know Monotone Continuity axiom due to Arrow (1970) is equivalent to the conditions saying that probabilities in the set of multiple priors C are all countably additive, provided is a  $\sigma$ -algebra<sup>11</sup>.

Fortunately, the monotone continuity axiom also ensure in our main result that only countably additive probabilities matter. Formally, the monotone continuity axiom follows as:

(Axiom 7) Monotone Continuity: We say that a preference relation  $\succeq$  on  $\mathcal{F}$  is monotone continuous if for all consequences  $x, y, z \in X$  such that  $y \succ z$ , and for all sequences of events  $\{A_n\}_{n\geq 1}$  with  $A_n \downarrow \emptyset$ , there exists  $k \geq 1$  such that  $y \succeq xA_k z$ .

**Proposition 5** Let  $\succeq$  be a preference relation as in Theorem 1. The following statements are equivalents:

- (i) The preference relation also satisfies the monotone continuity axiom,
- (ii) The set dom  $(\eta^*)$  consists only of countably additive probabilities.

### 4.2 A Characterization of Ambiguity Levels

For the precise result concerning the characterization of  $\eta$  on the main result as a ambiguity level we need the following definition:

**Definition 6** (Ghirardato, Maccheroni and Marinacci, 2004) We say that the preference relation  $\succeq_1$  reveals more ambiguity than  $\succeq_2$  if for any acts f and g

$$f \succeq_1 g \Rightarrow f \succeq_2 g$$

The decision maker 2 (with utility index  $u_2$  and ambiguity index  $\eta_2^*$ ) has a richer unambiguous preference than the decision maker 1 (with utility index  $u_1$  and ambiguity index  $\eta_1^*$ ) because the decision maker 2 behaves as if he is better informed about the decision problem.

<sup>&</sup>lt;sup>11</sup>See, for instance, Proposition B.1 of Ghirardato, Maccheroni and Marinacci (2004).

**Proposition 7** The following statements are equivalents:

a) The preference relation  $\succeq_1$  reveals more ambiguity than  $\succeq_2$ 

b) Both decision makers has the same attitudes towards risk (w.l.g,  $u_1 = u_2$ ) and  $\eta_1^* \leq \eta_2^*$ .

Now, consider that the subjective expected utility is the benchmark for absence of ambiguity. We say that preference relation  $\succeq$  reveals ambiguity when such preference reveals more ambiguity than some subjective expected utility preference  $\succeq_{SEU}$ . As consequence of the Proposition 7 and by  $\{\eta = 0\} \neq \emptyset$ , the class of preferences characterized in Theorem 1 reveals ambiguity.

## 5 Connecting with Variational Preferences<sup>12</sup>

Gilboa, Maccheroni, Marinacci and Schmeidler (2008) proposed a model where a decision maker is characterized by two preference relations capturing decisions that can be labeled in terms of rationality as objective or subjective, where the first is modeled through the Bewley's unanimity rule and the second via the Gilboa and Schmeidler's maxmin rule, both with respect to the same set of multiple priors C.

The key axioms are Consistency and Caution or, using a stronger condition, Default to Certainty<sup>13</sup>. Given two preference relations  $\succeq^*$  and  $\succeq^{**}$ , for any  $f, g \in \mathcal{F}$  and  $x \in X$ :

- Consistency:  $f \succeq^* g$  implies  $f \succeq^{**} g$ .
- Default to Certainty: If not  $f \succeq^* x$  then  $x \succ^{**} f$ .

The next result can be viewed as proving a novel foundation for variational preferences of MMR (2006), based on the interplay of the two preferences  $\succeq^*$  and  $\succeq^{**}$ . Note that variational representation of preferences can be derived without assuming the Uncertainty Aversion axiom<sup>14</sup> of Gilboa and Schmeidler (1989) and without the Weak Certainty Independence<sup>15</sup> axiom of MMR (2006).

<sup>14</sup> Uncertainty Aversion: For every  $f, g \in F$ , if  $f \sim g$  then  $(1/2) f + (1/2) g \succeq g$ .

<sup>15</sup>Weak Certainty Independence: If  $f, g \in F, x, y \in X$ , and  $\alpha \in (0, 1)$ , if

$$\alpha f + (1 - \alpha) x \succeq \alpha g + (1 - \alpha) x$$

then

$$\alpha f + (1 - \alpha) y \succeq \alpha g + (1 - \alpha) y$$

 $<sup>^{12}\,{\</sup>rm I'm}$  very grateful to Fabio Maccheroni for discussions and suggestions regarding the result in this section.

 $<sup>^{13}{\</sup>rm We}$  use only Default to Certainty in our result which justify why we pay attantion only to the stronger version of Caution.

**Theorem 8** Let  $\succeq^*$  be a variational Bewley preference represented by a pair  $(u, \eta^*)$  and  $\succeq^{**}$  be a complete continuous preorder. If  $\succeq^*$  and  $\succeq^{**}$  jointly satisfy Consistency and Default to Certainty then

$$f \succeq^{**} g \text{ iff } \min_{p \in \Delta} \int u(f) \, dp + \eta^{*}(p) \ge \min_{p \in \Delta} \int u(g) \, dp + \eta^{*}(p) = 0$$

Furthermore, for any prior  $p \in \Delta$ 

$$\sup_{f \gtrsim^* g} \left\{ \int \left( u\left(g\right) - u\left(f\right) \right) dp \right\} = \sup_{f \sim^{**} x} \left\{ u\left(x\right) - \int u\left(f\right) dp \right\}$$

The last formula provides the connection that exists between both preferences through the common ambiguity index.

## 6 Special Cases

In this section we study in some more detail special classes of variational Bewley preferences: the Knightian uncertainty model of Bewley (2002) and some preferences we just introduced, e.g., the incomplete and intransitive entropic preferences.

### 6.1 Bewley Incomplete Preferences

Begin with the Knightian uncertainty model axiomatized by Bewley (2002). As we mentioned in Introduction, the Bewley model is characterized by transitivity, an axiom that we dropped in our main result. Next we show in detail the relationship between transitivity and our main decision rule obtained in Theorem 1. In particular, when we add transitivity, the only probabilities in  $\Delta$  that matter are those to which the decision maker attributes maximum plausibility that is, those in  $\{\eta^* = 0\}$ , otherwise probabilities presents null plausibility, *i.e.*,  $\Delta = \{\eta^* = 0\} \cup \{\eta^* = \infty\}$ . Also, note that transitivity implies that every probability that matter has the same degree of plausibility.

**Proposition 9** Let  $\succeq$  be a variational Bewley preference. The following conditions are equivalent:

(i) The preference  $\succeq$  satisfies transitivity; (ii) For all  $f, g \in \mathcal{F}$ 

$$f \succeq g \text{ iff } \int u(f)dp \ge \int u(g)dp, \text{ for any } p \in \{\eta^* = 0\};$$

(iii) The function  $\eta^*$  takes on only values 0 and  $\infty$ .

### 6.2 Divergence Bewley preferences

We now introduce a new class of variational Bewley preferences that play an important role in the rest of this section. Assume there is an underlying probability measure  $q \in \Delta^{\sigma}$ . Given a convex continuous function  $\phi : \mathbb{R}_+ \to \mathbb{R}_+$  such that  $\phi(1) = 0$  and  $\lim_{t\to\infty} \phi(t)/t = 1$ , the  $\phi$ -divergence of  $p \in \Delta$  with respect to q is given by

$$D_{\phi}(p \parallel q) = \begin{cases} \int \phi\left(\frac{dp}{dq}\right) dq, \text{ if } p \in \Delta^{\sigma}(q) \\ \infty, \text{ otherwise.} \end{cases}$$

The mappings  $D_{\phi}(\cdot \parallel \cdot)$  are well known as standard divergences, which are a widely used notion of distance between distributions in statistics and information theory<sup>16</sup>. The two most important divergences are the *relative* entropy given by  $\phi(t) = t \ln t - t + 1$ , and the *relative Gini concentration index* given by  $\phi(t) = (t-1)^2/2$ .

The next lemma due to Maccheroni et. al. (2006) presents some important properties of divergences.

**Lemma 10** A divergence  $D_{\phi}(\cdot || q) : \Delta \to [0, \infty]$  is a grounded, convex, and lower semicontinuous function, and the sets  $\{p \in \Delta : D_{\phi}(p || q) \leq t\}$  are weakly compact subsets of  $\Delta^{\sigma}(q)$  for all  $t \in \mathbb{R}$ .

Thanks to the above properties, preferences  $\succeq$  on  $\mathcal{F}$  that satisfies the following rule

$$f \succeq g \Leftrightarrow \int \left\{ u(f) - u(g) \right\} dp \ge -\theta D_{\phi} \left( p \parallel q \right), \, \forall p \in \Delta,$$

where  $\theta > 0$  and  $u : X \to \mathbb{R}$  is an affine function, belong to the class of variational Bewley preferences. In view of their interesting properties, we call them *divergence Bewley preferences*.

**Theorem 11** Divergence Bewley preferences are monotone continuous variational Bewley preferences with index of ambiguity level given by

$$\eta^*: p \in \Delta \to \theta D_\phi \left( p \parallel q \right)$$

Concerning the analysis of comparative attitudes, the next simple consequence of Proposition 7 shows that they depend only on the parameter  $\theta$ , which can therefore be interpreted as a coefficient of ambiguity level. In order to be more specific about  $\phi$ , we speak of  $\phi$ -divergence Bewley preferences.

**Corollary 12** Given two  $\phi$ -divergence Bewley preferences  $\succeq_1$  and  $\succeq$ , the following statements are equivalents:

a) The preference relation  $\succeq_1$  reveals more ambiguity than  $\succeq_2$ 

b) Both decision makers has the same attitudes towards risk (w.l.g,  $u_1 = u_2$ ) and  $\theta_1 \leq \theta_2$ .

<sup>&</sup>lt;sup>16</sup>Csiszár (1963) introduced the notion of  $\phi$ -divergences  $D_{\phi}(\cdot \| \cdot)$  for probability measures and Liese and Vajda (1987) extended  $\phi$ -divergences  $D_{\phi}(\cdot \| \cdot)$  to finite or infinite measures.

This result says that divergence Bewley preferences become revealing more and more (less and less, resp.) ambiguity as the parameter becomes closer and closer to 0 (closer and closer to  $\infty$ , resp.). In fact, since for any  $p \in \Delta^{\sigma}(q)$ 

$$\lim_{\theta \to \infty} \theta D_{\phi} \left( p \parallel q \right) = \begin{cases} \infty, \text{ if } p \neq q \\ 0, \text{ if } p = q \end{cases}$$

we obtain that divergence Bewley preferences tend, more and more, as  $\theta \to \infty$ , to rank acts according to the SEU criterion with subjective probability q. On the other hand, since for any  $p \in \Delta^{\sigma}(q)$ 

$$\lim_{\theta \to 0} \theta D_{\phi} \left( p \parallel q \right) = 0,$$

we obtain that divergence Bewley preferences tend more and more,  $\theta \to 0$ , to rank acts according to the very cautious criteria. For example, when q has a finite support supp(q) such cautious criteria says that<sup>17</sup>

$$f \succeq g \text{ iff } u(f(s)) \ge u(g(s)), \forall s \in \text{supp}(q)$$

We commented that the two most important divergences are the relative entropy and the relative Gini concentration index given, which motivates the following examples:

**Example 13** If  $\eta = \theta R(\cdot || q) : \Delta \to [0, \infty]$ , where  $q \in \Delta^{\sigma}$  ( $\sigma$ -additive probability) and

$$R(p \parallel q) = \begin{cases} \int \log\left(\frac{dp}{dq}\right) dp \ if \ p \ll q\\ \infty, \ otherwise \end{cases}$$

is the relative entropy index (w.r.t q), we obtain a preference relation in a similar spirit of Hansen and Sargent (2001)'s robustness model, but with a decision rule a la Bewley, which we dub as relative entropic Bewley preferences.

**Example 14** if  $\eta = \theta G(\cdot \parallel q) : \Delta \to [0, \infty]$ , where  $q \in \Delta^{\sigma}$  and

$$G(p \parallel q) = \begin{cases} \frac{1}{2} \int \left(\frac{dp}{dq} - 1\right)^2 dq & \text{if } p \ll q\\ \infty, & \text{otherwise} \end{cases}$$

is the classic concentration Gine index, which is related to the well known model proposed by Tobin (1958) and Markowitz (1952). In fact, MMR(2006) showed that such ambiguity index for variational preferences entails the Tobin and Markowitz preference. We say that  $\succeq$  is a Gine Bewley preference if  $\succeq$  is a divergence Bewley preference for which  $\theta G(\cdot || q)$  is the ambiguity index.

 $<sup>^{17}\</sup>mathrm{For}$  the general case we need to assume some topological struture on the state spade because

 $<sup>\</sup>operatorname{supp}(q) := \cap \{ E \subset S : E \text{ is closed and } q(E^c) = 0 \}$ 

### 6.3 More Examples

Completing the list of examples we proposed two cases not included as Bewley multiple prior preferences or divergence Bewley preferences:

**Example 15** If  $\eta = \theta R (\cdot \parallel C) : \Delta \to [0, \infty]$ , where  $q \in \Delta^{\sigma}$  and

$$R\left(p \parallel C\right) = \inf_{q \in C} R\left(p \parallel q\right)$$

is the relative entropy index w.r.t.  $C^{18}$ , we obtain an interesting generalization of entropic Bewley preferences. In fact, note that if C is not a singleton it means that the decision maker has a multiple set of full plausible priors and such decision maker reveals more ambiguity that any decision maker a la entropic Bewley preferences with same parameter  $\theta$  and reference prior q belonging to C.

**Example 16** Now we consider a example without any requirement of countable additivity. Consider the mapping  $\eta = Fo\xi_v(\cdot) : \Delta \to [0,\infty]$ , where  $F : [0,1] \to \mathbb{R}_+ \cup \{+\infty\}$  is an increasing convex functions with F(0) = 0,  $v : \Sigma \to [0,1]$  is a convex capacity<sup>19</sup>, and

$$\xi_{v}\left(p\right) = \sup_{E \in \Sigma} \left\{ v\left(E\right) - p\left(E\right) \right\}, \; \forall p \in \Delta$$

is the plausibility index w.r.t. the capacity v. In this case, the set of full plausible priors is the core of the capacity v, in fact

$$\xi_{v}(p) = 0 \Leftrightarrow p \in core(v).$$

## 7 Appendix

We recall that  $B_0(\Sigma)$  is the vector space generated by the indicator functions of the elements of  $\Sigma$ , endowed with the supnorm. We denote by  $ba(\Sigma)$  the Banach space of all finitely additive set functions on  $\Sigma$  endowed with the total variation norm, which is isometrically isomorphic to the norm dual of  $B_0(\Sigma)$ , so, in this case the weak<sup>\*</sup> topology  $\sigma$  ( $ba.B_0$ ) of  $ba(\Sigma)$  coincides with the event-wise convergence topology.

Given a binary relation  $\succeq$  on  $B_0(\Sigma)$ , some properties follows as:

 $^{19}\mathrm{A}$  capacity satisfies

c) For any  $A, B \in \Sigma$ ,

 $v(A \cup B) + v(A \cap B) \ge v(A) + v(B).$ 

Also, the core of v is given by

 $core\left(v\right) := \left\{p \in \Delta : p\left(E\right) \ge v\left(E\right), \forall E \in \Sigma\right\}.$ 

<sup>&</sup>lt;sup>18</sup>See Lemma 4 (page 41) of Strzalecki (2007).

a)  $v(\emptyset) = 0, v(S) = 1;$ 

b)  $A \subset B \Rightarrow v(A) \leq v(B);$ 

Convexity means (note that c implies b)

- $\succeq$  is *reflexive* if  $a \succeq a$  for every  $a \in B_0(\Sigma)$ ;
- $\succeq$  is transitive whenever  $a, b, c \in B_0(\Sigma)$ , if  $a \succeq b$  and  $b \succeq c$  then  $a \trianglerighteq c$ ;
- $\succeq$  is non-trivial if the exists  $a, b \in B_0(\Sigma)$  such that  $a \succeq b$  but not  $b \succeq a$ (in this case we wrote  $a \triangleright b$ );
- $\geq$  is Archimedean continuous if for all  $a, b, c \in B_0(\Sigma)$  the sets

$$\{\alpha \in [0,1] : \alpha a + (1-\alpha) b \ge c\}$$

and

$$\{\alpha \in [0,1] : c \trianglerighteq \alpha a + (1-\alpha) b\}$$

are closed in [0, 1];

•  $\succeq$  is convex-affine if for all  $a, b, c_1, c_2 \in B_0(\Sigma)$  and  $\alpha \in (0, 1)$  such that  $c_1 \ge c_2$ ,

$$a \ge b$$
 then  $\alpha a + (1 - \alpha) c_1 \ge \alpha b + (1 - \alpha) c_2;$ 

- $\succeq$  is monotonic if  $a \ge (>) b$  then  $a \ge (\triangleright) b$ ;
- $\succeq$  is monotonic continuous if for any  $r_1, r_2, t \in \mathbb{R}$  such that  $r_1 \mathbf{1}_S \triangleright r_2 \mathbf{1}_S$ and for all sequences of events  $\{A_n\}_{n>1}$  with  $A_n \downarrow \emptyset$ , there exists  $n_0 \ge 1$ such that  $r_1 1_S \supseteq x A_{n_0} z$ .
- $\succeq$  is satisfies dominance if  $a \succeq b$  and  $c \ge a$  then  $c \trianglerighteq b$ .

**Lemma 17** A reflexive, affine and monotonic binary relation  $\succeq$  on  $B_0(\Sigma)$  is continuous if and only if it is Archimedian.

**Proof.** The proof follows from Gilboa, Maccheroni, Marinacci and Schmeidler (2008): In fact, they showed that an affine and monotonic preorder is continuos if and only if it is Archimedean. First, we note that it is obvious that if  $\geq$  is convex then  $\triangleright$  affine because  $\triangleright$  is reflexive. So, we can mimic Lemma 1 (page 32), Lemma 2 (page 33)<sup>20</sup>, and Lemma 3 (page 35) without transitivity.

Theorem 1:

**Proof.**  $(1) \Rightarrow (2)$ :

By Axiom 2, Axiom 3 and Axiom 5 the restriction of  $\succeq$  on  $X \times X$  satisfies the set of the von Neumann-Morgenstern (1944)'s axioms and then there exist a non constant function  $u: X \to \mathbb{R}$  such that  $x \succeq y$  if and only if  $u(x) \ge u(y)$ such that for any  $x, y \in X$  and  $\alpha \in (0, 1)$ ,

$$u(\alpha x + (1 - \alpha) y) = \alpha u(x) + (1 - \alpha) u(y),$$

*i.e.*, u is an affine function. Moreover, u is unique up to positive linear transformation<sup>21</sup>. Also, an important fact comes from the Axiom 6 about Unboundedness, in fact, we obtain that  $u(X) = \mathbb{R}$  (see, for instance, MMR 2006).

 $<sup>^{20}</sup>$ Concerning Lemma 2, note that in our case K is the whole set of real numbers, which is not an important assumption for this result. <sup>21</sup>See, for instance, section 2.2 of Föllmer and Schied (2004).

Now we define the binary relation  $\succeq$  over the set  $B_0(\Sigma) = \{u(f) : f \in \mathcal{F}\}$  by:

$$a \ge b \Leftrightarrow f \succeq g$$
, for some  $f, g \in \mathcal{F}$  such  $a = u(f)$  and  $b = u(g)$ .

We note that  $\succeq$  is well defined on  $B_0(\Sigma)$  and

$$a \ge b \Leftrightarrow f \succeq g$$
, for any  $f, g \in \mathcal{F}$  such  $a = u(f)$  and  $b = u(g)$ .

We note that  $\succeq$  is:

Reflexive: Given  $a \in B_0(\Sigma)$  we have that a = u(f) for some  $f \in \mathcal{F}$ , and since  $\succeq$  is reflexive  $f \succeq f$  which implies that  $a \succeq a$ ;

Non-trivial: We know that  $\succeq$  is non-trivial because there exists  $x, y \in X$  such that  $x \succeq y$  but not  $y \succeq x$ , so by considering the constant functions  $a := u(x)1_S$  and  $b := u(y)1_S$  on  $B_0(\Sigma)$  we have that  $a \succeq b$  but not  $b \succeq a$ , *i.e.*,  $a \succ b$ ;

Convex-affine: Consider  $a, b, c_1, c_2 \in B_0(\Sigma)$  and  $\alpha \in (0, 1)$  such that  $c_1 \geq c_2$ . Hence there exist  $f, g, h_1, h_2$  such that  $a = u(f), b = u(g), c_1 = u(h_1)$ , and  $c_2 = u(h_2)$ , in particular  $h_1 \succeq h_2$ . Since  $\succeq$  satisfies the dominance independence,

$$a \ \ \ b \Leftrightarrow f \succeq g \Leftrightarrow \alpha f + (1 - \alpha) h_1 \succeq \alpha g + (1 - \alpha) h_2 \\ \Leftrightarrow \ \ u \left(\alpha f + (1 - \alpha) h_1\right) \supseteq u \left(\alpha g + (1 - \alpha) h_2\right) \\ \Leftrightarrow \ \ \alpha a + (1 - \alpha) c_1 \supseteq \alpha b + (1 - \alpha) c_2.$$

Archimedean continuous: Consider a = u(f), b = u(g), and  $c = u(h) \in B_0(\Sigma)$ , then

$$\begin{aligned} \{\alpha \in [0,1] : \alpha a + (1-\alpha) \, b \ge c\} &= \{\alpha \in [0,1] : \alpha u(f) + (1-\alpha) \, u(g) \ge u(h)\} \\ &= \{\alpha \in [0,1] : u(\alpha f + (1-\alpha) \, g) \ge u(h)\} \\ &= \{\alpha \in [0,1] : \alpha f + (1-\alpha) \, g \succsim h\}, \end{aligned}$$

is closed in [0, 1] because the Archimedean Continuity of  $\succeq$ , and a similar argument shows that  $\{\alpha \in [0, 1] : c \geq \alpha a + (1 - \alpha) b\}$  is closed too.

Monotonic: If  $a = u(f) \ge (>) b = u(g)$  then  $f(s) \succeq (\succ) g(s)$  for any  $s \in S$  and the monotonicity of  $\succeq$  implies that  $f \succeq (\succ) g$ , hence  $a \ge (\rhd) b$ .

We note also that  $\succeq$  satisfies *dominance*: In fact, if there exist  $a, b, c \in B_0(\Sigma)$ such that  $a \succeq b$  and  $c \ge a$  with not  $c \succeq b$  then we obtain a point  $(c, b) \notin \trianglerighteq$  and since  $\succeq$  is closed and convex subset of  $B_0(\Sigma) \times B_0(\Sigma)$ , by separation argument (see, for details, footnote 22 on the end of this proof) we can found  $q \in \Delta$  such that

$$\int (b-c) \, dq > \sup_{(d_1,d_2) \in \succeq} \int (d_2 - d_1) \, dq \ge \int (b-a) \, dq,$$

which implies that  $\int cdq < \int adq$  which is impossible because  $c \ge a$ .

Now we define a very useful mapping  $\eta^* : \Delta \to \mathbb{R} \cup \{+\infty\}$  for our representation and it is given by the following rule: for any probability  $p \in \Delta$ ,

$$\eta^*(p) = \sup_{(f,g)\in \succeq} \left( \int \left( u(g) - u(f) \right) dp \right) = \sup_{(a,b)\in \succeq} \left( \int \left( b - a \right) dp \right).$$

Since  $(a, a) \in \supseteq$  for each  $a \in B_0(\Sigma)$ , it is true that  $\eta^*(p) \ge \left(\int (a - a) dp\right) = 0$ , i.e.,  $\eta^*$  is a *non-negative* function.

Now, we define the mapping:

$$(\Delta \times \geq) \ni (p, (a, b)) \mapsto \rho_{(a, b)}(p) = \int (b - a) dp$$

Clearly, for each  $(a, b) \in \mathbb{P}$  the function  $\rho_{(a,b)}(\cdot) : \Delta \to \mathbb{R}$  is linear and weak<sup>\*</sup> continuous. Also, since the supremum of continuous (lower semicontinuous function) is lower semicontinuous<sup>22</sup> we have that

$$\eta^{*}\left(\cdot\right) = \sup_{(a,b)\in \succeq} \rho_{(a,b)}\left(\cdot\right)$$

is weak<sup>\*</sup> lower semicontinuous. Moreover,  $\eta^*$  is convex because the supremum of linear functions is a convex function<sup>23</sup>.

Now we intent to show that  $\{\eta = 0\} \neq \emptyset$ . First we will show that  $\inf_{p \in \Delta} \eta^*(p) = 0$  and for this part of the proof we need the following result:

von Neumann's minimax theorem<sup>24</sup>: Let M and N be convex subsets of vector spaces supplied with topologies If M is compact and  $\phi: M \times N$  satisfy: i) for any  $y \in N$ ,  $M \ni x \mapsto \phi(x, y)$  is convex and lower semicontinuous;

i) for any  $y \in N$ ,  $M \not\ni x \mapsto \phi(x, y)$  is concave. ii) for any  $x \in M$ ,  $N \not\ni y \mapsto \phi(x, y)$  is concave. Then

$$\inf_{x \in M} \sup_{y \in N} \phi(x, y) = \sup_{y \in N} \inf_{x \in M} \phi(x, y).$$

In our case  $M = \Delta$  and  $N = \supseteq$ . We note since  $\supseteq$  is s-affine, if  $(a, b) \in \supseteq$  and  $(c_1, c_2) \in \supseteq$  then for any  $\beta \in [0, 1]$ , we have that

$$(\beta a + (1 - \beta) c_1, \beta b + (1 - \beta) c_2) \in \succeq,$$

*i.e.*,  $\succeq$  is a convex subset of  $B_0(\Sigma)^2$  and, clearly,  $\Delta$  is a convex subset of  $ba(\Sigma)$ . Also, by the Banach-Alaoglu-Bourbaki theorem<sup>25</sup>,  $\Delta$  is a weak<sup>\*</sup> compact subset of  $ba(\Sigma)$ . By what we have observed  $\eta^*$  is convex and weak<sup>\*</sup> lower semicontinuous. Moreover, it is easy to see that the function

$$(a,b) \mapsto \rho_{(a,b)}(p) = \int (b-a) dp$$

is affine (hence concave) for each  $p \in \Delta$ . Hence, by the minimax theorem and the fact that (by monotonicity)  $(a, b) \in \supseteq$  implies that  $a(s_0) \ge b(s_0)$  for some

<sup>&</sup>lt;sup>22</sup>See, for instance, Brézis (1984), page 8.

 $<sup>^{23}</sup>$  See, for instance, Brézis (1984), page 9.

<sup>&</sup>lt;sup>24</sup> The proof of this classical result can be found in Aubin and Ekeland (1984), chapter 6.

 $<sup>^{25}</sup>$  See, for instance, Brézis (1984) page 42.

$$\inf_{p \in \Delta} \sup_{(a,b) \in \succeq} \left( \int (b-a) \, dp \right) = \sup_{\substack{(a,b) \in \succeq \\ p \in \Delta}} \inf_{p \in \Delta} \left( \int (b-a) \, dp \right) = \sup_{\substack{(a,b) \in \succeq \\ \underbrace{s \in S} \\ \leq 0}} \inf_{s \in S} \left( b \left( s \right) - a \left( s \right) \right) \stackrel{(\succeq \text{ is reflexive})}{=} 0.$$

Now we will show that there exists some  $q \in \Delta$  such that  $\eta^*(q) = 0$ . Since  $\eta^*(q) \ge 0$ , it is enough to show that there exists  $q \in \Delta$  such that  $\eta^*(q) \le 0$ , *i.e.*, it is possible to find  $q \in \Delta$  such that

$$\int (a-b) \, dp \ge 0 \text{ for any } (a,b) \in \trianglerighteq$$

Denoting  $E = B_0(\Sigma)$  and  $E^*$  its dual, then our problem is to find some  $x^* \in E^*$  such that

$$\begin{array}{rcl} \langle x^*, 1_S \rangle & \geq & 1 \\ \langle x^*, -1_S \rangle & \geq & -1 \\ \langle x^*, a - b \rangle & \geq & 0, \text{ for any } (a, b) \in \unrhd \end{array}$$

The mathematical tool for this kind of problem was given by Fan (1956), page 126:

Ky Fan's theorem: Given an arbitrary set  $\Lambda$ , let the system

$$\langle x^*, x_i \rangle \ge \alpha_i, i \in \Lambda$$
 ( $\Xi$ )

of linear inequalities; where  $\{x_i\}_{i \in \Lambda}$  be a family of elements, not all 0, in real normed linear space E, and  $\{\alpha_i\}_{i \in \Lambda}$  be a corresponding family of real numbers. Let  $\sigma := \sup \sum_{j=1}^n \lambda_j \alpha_{i_j}$  when  $n \in N$ , and  $\lambda_j$  vary under conditions:  $\lambda_j \ge 0$ ,  $\forall i \in \{1, \dots, n\}$  and  $\|\sum_{j=1}^n \lambda_j x_j\|_{j=1}^n = 1$ . Then the system  $(\Xi)$  has a solution

 $\forall j \in \{1, ..., n\}$  and  $\left\| \sum_{j=1}^{n} \lambda_j x_{i_j} \right\|_{E} = 1$ . Then the system ( $\Xi$ ) has a solution  $x^* \in E^*$  if and only if  $\sigma$  is finite.

Let us consider  $\lambda_1, \lambda_2, ..., \lambda_n \ge 0$  and  $\mathbf{1}_S, -\mathbf{1}_S, (a_j, b_j) \in \mathbb{D}, 3 \le j \le n$  such that:

$$\left\|\lambda_1 \mathbf{1}_S + \lambda_2 (-\mathbf{1}_S) + \sum_{j=3}^n \lambda_j (a_j - b_j)\right\|_{\infty} = 1,$$

it follows that

$$\lambda_1 \mathbf{1}_S - \lambda_2 \mathbf{1}_S + \sum_{j=3}^n \lambda_j \ (a_j - b_j) \le \mathbf{1}_S,$$

 $s_0$ :

hence,

$$\lambda_1 - \lambda_2 + \sum_{j=3}^n \lambda_j \int (a_j - b_j) dp \le 1 \text{ for any } p \in \Delta,$$

since

$$-\eta^{*}(p) = \inf_{(a,b)\in \unrhd} \left( \int (a-b) dp \right),$$

we obtain that

$$\lambda_1 - \lambda_2 - \eta^*(p) \sum_{j=3}^n \lambda_j \le 1 \text{ for any } p \in \Delta,$$

we saw that  $\inf_{p \in \Delta} \eta^*(p) = 0$ , hence  $\sup_{p \in \Delta} \{-\eta^*(p)\} = 0$  and,

$$\lambda_1 - \lambda_2 = \lambda_1 - \lambda_2 + \sup_{p \in \Delta} \left( -\eta^* \left( p \right) \right) \sum_{j=3}^n \lambda_j \le 1,$$

*i.e.*,  $\sum_{j=1}^{n} \lambda_j \alpha_j \leq 1$ ; where  $\alpha_1 = 1$ ,  $\alpha_2 = -1$ , and  $\alpha_j = 0$ ,  $3 \leq j \leq n$ . Hence  $\sigma$  is finite and by Ky Fan's theorem there exists  $q \in \Delta$  such that  $\eta^*(q) = 0$ .

For the last statement in the theorem note that if  $f_0 \succeq g_0$  then  $\eta^*(p) \ge$  $\int (u(g_0) - u(f_0)) dp$  for any  $p \in \Delta$ , hence

$$\int u(f_0)dp + \eta^*(p) \ge \int u(g_0)dp \text{ for any } p \in \Delta.$$

Conversely, if  $(f_0, g_0) \notin \gtrsim$  then  $(a_0, b_0) \notin \supseteq$ , where  $a_0 = u(f_0)$  and  $b_0 = u(g_0)$ . Since  $\geq$  is a nonempty, convex (by dominance independence) and closed (by Lemma 17) subset of  $B_0(\Sigma) \times B_0(\Sigma)$ . Using the separation theorem<sup>26</sup> there exists  $q \in \Delta$  that defines the linear functional  $\Psi((a,b)) = \int (b-a) dq$  over  $B_0(\Sigma) \times B_0(\Sigma)$ , and<sup>27</sup>

$$\int (b_0 - a_0) dq > \sup_{(a,b) \in \succeq} \int (b - a) dq = \eta^* (q),$$

 $\frac{^{26}\text{See, for instance, the theorem I.7 at page 7 in Brézis (1984).}}{^{27}\text{In fact, since by Schatten (1950), } (B_0(\Sigma) \times B_0(\Sigma))^* = B_0(\Sigma)^* \times B_0(\Sigma)^* \text{ we obtain that}} \\
\Psi((a,b)) = \int bdq_1 - \int adq_2 \text{ with } q_1, q_2 \in ba(\Sigma). \text{ Since } (a,a) \in \mathbb{D} \text{ for all } a \in B_0(\Sigma) \text{ we obtain } bdq_1 - \int adq_2 \text{ with } q_1, q_2 \in ba(\Sigma).$ that  $\Psi((a, a)) = 0$ ; in fact, if  $\Psi((a, a)) \neq 0$  we obtain that

$$\sup_{k \in \mathbb{Z}} \Psi\left( (ka, ka) \right) = \infty$$

but

$$\Psi\left(\left(a_{0},b_{0}
ight)
ight)>\sup_{k\in\mathbb{Z}}\Psi\left(\left(ka,ka
ight)
ight),$$

a contradiction. In particular,  $q_1 = -q_2$ . Also, we note that  $q_1 \ge 0$ ; if  $q_1(E) < 0$  for some  $E \in \Sigma$  by monotonicity we obtain that  $(nq_1(E) \mathbf{1}_S, 0) \in \mathbb{D}$  for any  $n \ge 1$  and

$$\Psi\left(\left(a_{0},b_{0}\right)\right) > \sup_{n}\left\{-nq_{1}\left(E\right)\right\} = \infty$$

a contradiction. Finally, w.l.g. we may suppose that  $q_1(S) = 1$ .

i.e., there exists  $q \in \Delta$  such that,

$$\int u(f_0)dq + \eta^*(q) < \int u(g_0)dq.$$

 $(2) \Rightarrow (1):$ 

It is straightforward.

That  $\eta^*$  is minimal is easy: in fact, if there exists a grounded, convex and lower semicontinuous function  $\gamma: \Delta \to [0, \infty]$  such that for any  $f, g \in \mathcal{F}$ ,

$$f \succeq g \Leftrightarrow \int u(f)dp + \gamma(p) \ge \int u(g)dp, \, \forall p \in \Delta,$$

then

$$\gamma(p) \ge \int u(g)dp - \int u(f)dp, \,\forall p \in \Delta \text{ and } \forall (f,g) \in \mathcal{L}$$

so, for any  $p \in \Delta$ 

$$\gamma(p) \ge \sup_{(f,g)\in \gtrsim} \left(\int u(g)dp - \int u(f)dp\right) = \eta^*(p)$$

Proof of Corollary 3:

**Proof.** Let  $(u, \eta^*)$  represent  $\succeq$  as in Theorem 1. Taking another representation  $(u_1, \eta_1^*)$  of  $\succeq$  as in Theorem 1, by its key equivalence u and  $u_1$  are affine representations of the restriction of  $\succeq$  to the set of consequence X. Hence, by a well known uniqueness results, there exists  $\alpha > 0$  and  $\beta \in \mathbb{R}$  such that  $u_1 = \alpha u + \beta$ . By the characterization of  $\eta^*$  obtained in Theorem 1 for any probability p,

$$\eta_1^*(p) = \sup_{(f,g)\in\gtrsim} \left( \int (u_1(g) - u_1(f)) \, dp \right)$$
$$= \sup_{(f,g)\in\gtrsim} \left( \int \alpha u(g) + \beta - (\alpha u(g) + \beta) \, dp \right)$$
$$= \sup_{(f,g)\in\gtrsim} \left( \int \alpha u(g) - \alpha u(g) \, dp \right) = \alpha \eta^*(p)$$

Proof of Proposition4:

**Proof.** Consider the asymmetric component  $\succ \subset \mathcal{F} \times \mathcal{F}$  induced from a variational Bewley preference  $\succeq$ . Since it is well know a sufficient condition for  $\succ$  to be acyclic is the existence of a real-valued function V on  $\mathcal{F}$  such that

$$f \succ g \Rightarrow V(f) > V(g) \,.$$

Now, consider

$$V(f) = \min_{p \in \Delta} \left( \int u(f) \, dp + \eta^*(p) \right),$$

if there exist acts f,g such that  $f\succ g$  and  $V\left(f\right)\leq V\left(g\right)$  then

$$\int u(f) dp + \eta^{*}(p) \geq \int u(g) dp, \forall p \in \Delta,$$
  

$$\exists p_{0} \in \Delta \text{ s.t. } \int u(g) dp_{0} + \eta^{*}(p_{0}) < \int u(f) dp_{0},$$
  
and 
$$\exists q_{1}, q_{2} \in \Delta \text{ s.t. } \int u(f) dq_{1} + \eta^{*}(q_{1}) \leq \int u(g) dq_{2} + \eta^{*}(q_{2}).$$

Hence, since  $\eta$  is convex, for any  $n \in \mathbb{N}$ ,

$$\int u(f) d\left(\overbrace{n^{-1}q_{1} + (1 - n^{-1})p_{0}}^{:=q_{1}np_{0}}\right) + \eta^{*}(q_{1}np_{0})$$

$$\leq \int u(f) d(q_{1}np_{0}) + n^{-1}\eta^{*}(q_{1}) + (1 - n^{-1})\eta^{*}(p_{0})$$

$$\leq \int u(g) d(q_{2}np_{0}) + n^{-1}\eta^{*}(q_{2}) + (1 - n^{-1})\eta^{*}(p_{0})$$

which entails,

$$\int u(g) dp_0 + \eta^*(p_0)$$

$$= \lim \inf_{n \to \infty} \left\{ \int u(g) d(q_2 n p_0) + n^{-1} \eta^*(q_2) + (1 - n^{-1}) \eta^*(p_0) \right\}$$

$$\geq \lim \inf_{n \to \infty} \left\{ \int u(f) d(q_1 n p_0) + \eta^*(q_1 n p_0) \right\}$$

$$\geq \lim \inf_{n \to \infty} \int u(f) d(q_1 n p_0) + \lim \inf_{n \to \infty} \eta^*(q_1 n p_0)],$$

Since  $\eta^*$  is weak<sup>\*</sup> lower semi-continuous and  $(q_1 n p_0)(E) \to p_0(E)$  for any  $E \in \Sigma$ , we obtain

$$\int u(g) \, dp_0 + \eta^*(p_0) \ge \int u(f) \, dp_0 + \eta^*(p_0) > \int u(f) \, dp_0,$$

a contradiction. Hence,  $f \succ g \Rightarrow V(f) > V(g)$  and  $\succ$  is acyclic.

**Lemma 18** Consider a preference relation  $\succeq$  as in Theorem 1 and some particular utility index  $u: X \to \mathbb{R}$  consistent with  $\succeq|_{X \times X}$ . For any  $f, g \in \mathcal{F}$  there exists a minimal  $c_{(f,g)} \ge 0$  such that for any  $c \ge c_{(f,g)}$ 

$$f \succeq g \text{ iff } \int u(f)dp + \eta^*(p) \ge \int u(g)dp, \text{ for any } p \in \{\eta^* \le c\}.$$

In fact,  $c_{(f,g)} = \sup uog - \inf uof$ .

**Proof.** The implication  $(\Rightarrow)$  is obvious. Now, suppose that

$$c \ge c_{(f,g)} = \sup uog - \inf uof$$

Now consider  $p \in \Delta$  such that  $\eta^*(p) \ge c_{(f,g)}$ . Since  $uoh \in [\inf uoh, \sup uoh]$  for  $h \in \{f, g\}$  we have that

$$uog - uof \in [\inf uog, \sup uog],$$

also,

$$\int \left(u(g) - u(f)\right) dp \le \left\|u(g) - u(f)\right\|_{\infty} \le \sup uog - \inf uof \le \eta^*\left(p\right).$$

Hence, if for some  $c \ge c_{(f,g)}$ 

$$\int u(f)dp + \eta^*(p) \ge \int u(g)dp, \text{ for any } p \in \{\eta^* \le c\}$$

then  $f \succeq g$ .

Proof of Proposition 5:

**Proof.** (i) implies (ii):

Let  $p \in ba(\Sigma) \setminus ca(\Sigma)$  be a non-countably additive probability. Hence there exists a sequence of events  $\{A_n\}_{n\geq 1}$  such that  $A_n \downarrow \emptyset$  and  $p(A_n) \downarrow \alpha > 0$ . So, since  $u(X) = \mathbb{R}$  for each  $n \geq 1$  there exists some  $x_n$  such that  $u(x_n) = n^{-1}$ . Consider  $z \in X$  such that u(z) = 0. Hence, monotonicity implies that  $x_n \succ z$ .

Now, by considering  $x_m \in \left\{ u^{-1} \left( (\alpha n)^{-1} + m \right) \right\}$ ,  $m \ge 1$ , we obtain by the monotonic continuity axiom that there exist k = k(n) such that

$$x_n \succeq x_m A_k z$$

Hence,

$$\eta^*(p) \geq \int \left(u\left(x_m A_k z\right) - u\left(x_n\right)\right) dp$$
  
=  $\left((\alpha n)^{-1} + m\right) p\left(A_k\right) - n^{-1}$   
=  $mp\left(A_k\right) + \frac{1}{n} \left(\frac{p\left(A_k\right)}{\alpha} - 1\right),$ 

so, for any  $m \ge 1$ 

$$\eta^{*}(p) \geq \lim_{n \to \infty} \left( mp(A_{k}) + \frac{1}{n} \left( \frac{p(A_{k})}{\alpha} - 1 \right) \right)$$
$$= \lim_{n \to \infty} mp(A_{k(n)}) + \lim_{n \to \infty} \frac{1}{n} \left( \frac{p(A_{k})}{\alpha} - 1 \right)$$
$$\geq m\alpha,$$

which implies that  $\eta^*(p) = \infty$ . Hence, if  $\eta^*(p) < \infty$  then  $p \in ca(\Sigma)$ .

(ii) implies (i):

Let  $x, y, z \in X$  such that  $y \succ z$  and a sequences of events  $\{A_n\}_{n\geq 1}$  with  $A_n \downarrow \emptyset$ . If  $y \succeq x$  we have by monotonicity (y statewise dominates  $xA_nz$ ) that  $y \succeq xA_nz \forall n \geq 1$ . On the other hand, consider the case where  $x \succ y$ . We need to show that there exists some  $n_0 \geq 1$  such that

$$y \succeq x A_{n_0} z$$

By the previous Lemma, choosing c = u(x) - u(y) + 1 it is enough to show that for any  $p \in \{\eta^* \le c\}$ ,

$$u(y) + \eta^*(p) \ge \int u(xA_nz) dp.$$

Recalling that  $\eta^*$  is weak<sup>\*</sup> lower semicontinous we have that  $\{\eta^* \leq c\}$  is a weak<sup>\*</sup> compact set of countably additive probabilities, so it is a weak compact subset of countably additive probabilities. By Theorem IV.9.1 of Dunford and Schwartz (1958) it follows that if  $\varepsilon > 0$  and  $A_n \downarrow \emptyset$  there exists  $n_o$  such that  $p(A_n) < \varepsilon$  for any  $n \geq n_0$  and all  $p \in \{\eta^* \leq c\}$ . Hence, putting  $\varepsilon = [u(y) - u(z) + \eta^*(p)] / [u(x) - u(z)]$  we know that there exists  $n_0$  such that

$$p(A_n) < [u(y) - u(z) + \eta^*(p)] / [u(x) - u(z)],$$

for any  $n \ge n_0$  and for any  $p \in \{\eta^* \le u(x) - u(y)\}$ . Hence, for any p such that  $\eta^*(p) \le c$ 

$$u(y) + \eta^{*}(p) > p(A_{n})u(x) + u(z)(1 - p(A_{n})) = \int u(xA_{n}z) dp,$$

and we conclude that  $y \succeq xA_n z$  for any  $n \ge n_0$ .

Proposition 7

**Proof.**  $a \Rightarrow b$  Concerning the same risk attitudes, it follows from Ghirardato et. al. (2004), Corollary B.3, i.e., we can take  $u_1 = u_2 = u$ .

By assumption  $f \succeq_1 g \Rightarrow f \succeq_2 g$ , i.e.,  $\succeq_1 \subset \succeq_2$ . So, for any  $p \in \Delta$ :

$$\eta_1^*(p) = \sup_{\substack{(f,g)\in \gtrsim_1}} \left( \int \left( u(g) - u(f) \right) dp \right)$$
  
$$\leq \sup_{\substack{(f,g)\in \gtrsim_2}} \left( \int \left( u(g) - u(f) \right) dp \right) = \eta_2^*(p)$$

b)  $\Rightarrow a$ ) Consider  $(f,g) \in \gtrsim_1$ , i.e.,  $\int u(f)dp + \eta_1^*(p) \ge \int u(g)dp, \forall p \in \Delta$ . Since  $\eta_2^* \ge \eta_1^*$ , we obtain that for any  $p \in \Delta$ ,

$$\int u(f)dp + \eta_2^*(p) \ge \int u(f)dp + \eta_1^*(p) \ge \int u(g)dp,$$

i.e.,  $f \succeq_2 g$ .

Theorem 8

**Proof.** By our assumption,  $\succeq^*$  is a variational Bewley preference represented by a pair  $(u, \eta^*)$ . We note that by Consistency

$$x \succeq^* y$$
 implies  $x \succeq^{**} y$ .

By Default to Certainty

$$x \succ^* y$$
 implies  $x \succ^{**} y$ .

Therefore,  $\succ^*$  and  $\succ^{**}$  coincide on X, and the mapping  $x \mapsto u(x)$  represents both preferences on X.

We note that  $\succ^{**}$  satisfies " $f(s) \succeq^{**} g(s) \forall s \in S$  implies  $f \succeq^{**} g$ ": In fact,  $f(s) \succeq^{**} g(s) \forall s \in S$  implies, by what we have just show,  $f(s) \succeq^{*} g(s)$ , which by Monotonicity of  $\succeq^{*}$  implies  $f \succeq^{*} g$ , and Consistency delivers  $f \succeq^{**} g$ .

Let  $x_f \in X$  be the certainty equivalent of f w.r.t.  $\succ^{**}$ . We note that by the continuity property of  $\succeq^{**}$ , for any  $f \in \mathcal{F}$  there exists such lottery  $x_f$ . Clearly

$$f \succeq^{**} g \text{ iff } u(x_f) \ge u(x_g)$$

So, for any act f, Default to Certainty delivers  $f \succeq^* x_f$ . Hence,

$$\int u(f) dp + \eta^*(p) \ge u(x_f), \text{ for any } p \in \Delta,$$

therefore,

$$u(x_f) \leq \min_{p \in \Delta} \int u(f) dp + \eta^*(p).$$

If the strictly inequality holds there exists  $y \in X$  such that

$$u(x_f) < u(y) < \min_{p \in \Delta} \int u(f) \, dp + \eta^*(p)$$

that is

$$f \succeq^* y \text{ and } y \succ^{**} x_f,$$

by Consistency

$$f \succeq^* y \text{ and } y \succ^{**} x_f,$$

and since  $\succeq^*$  is a preorder we obtain  $f \succ^{**} x_f$ , which is impossible.

### References

- Anscombe. F.J. and Aumann (1963): A definition of subjective probability, Annals of Mathematical Statistics, 34, 199-205.
- [2] Aubin, J.P. and I. Ekeland (1984): Applied Nonlinear Analysis, Wiley, New York.
- [3] Aumann, R. (1962): Utility theory without the completeness axiom. Econometrica, 30,445–462.

- [4] Bewley, T. (2002): Knightian decision theory: Part I. Decisions Econom. Finance, 25, 79-110. (First version: 1986).
- [5] Brézis, H. (1984): Análisis Funcional: Teoria y Aplicaciones. Alianza Editorial, Madrid.
- [6] Csiszár, I. (1963): Eine Informationstheoretische Ungleichung und ihre Anwendung auf den Bewis der Egodizität von Markoffschen Ketten. Publi. Math. Inst. Hung. Acad. Sci., Ser. A, 8, 85-108.
- [7] Chateauneuf, A. and J.H. Faro (2009): Ambiguity through confidence functions. Journal of Mathematical Economics, in press. (IMPA preprint service, A474, 2006).
- [8] Dubra, J., F. Maccheroni, and E. Ok (2004): Expected utility theory without the completeness axiom. Journal of Economic Theory, 115, 118–133.
- [9] Dunford, N. and J. T. Schwartz (1958): Linear Operators, Part I: General Theory. Wiley Classics Library Edition Published 1988.
- [10] Ellsberg, D. (1961):*Risk, ambiguity and the Savage axioms.* Quarterly Journal of Economics, 75, 643-669.
- [11] Fan, K.(1956): On systems of linear inequalities, in: Linear inequalities and related systems. Annals of Mathematical Studies, 38.
- [12] Fishburn, P.C. (1970): Utility Theory for Decision Making. John Wiley and Sons.
- [13] Föllmer, H. and A. Schied (2004): Stochastic Finance. An Introduction in Discrete Time, 2nd Edition. de Gruyter Studies in Mathematics 27.
- [14] Ghirardato, P., F. Maccheroni, M. Marinacci (2004): Differentiating ambiguity and ambiguity attitude. Journal of Economic Theory, 118, 133-173.
- [15] Ghirardato, P., F. Maccheroni, M. Marinacci, and M. Siniscalchi.(2003): A subjective spin on roulette wheels, Econometrica, 71, 1897-1908.
- [16] Gilboa, I., F. Maccheroni, M. Marinacci, and D. Schmeidler (2008): Objective and subjective rationality in a multiple prior model. mimeo.
- [17] Gilboa, I. and D. Schmeidler.(1989): Maxmin expected utility with a nonunique prior. Journal of Mathematical Economics, 18, 141-153.
- [18] Giroto, B. and S. Holzer (2005): Representation of subjective preferences under ambiguity. Journal of Mathematical Psychology, 49, 372-382.
- [19] Hansen, L. and T. Sargent.(2001): Robust control and model uncertainty. American Economic Review, 91, 60-66.

- [20] Knight, F. H.(1921): Risks, Uncertainty and Profit. Boston: Houghton-Mifflin.
- [21] Nascimento, L. and G. Riella (2008): A class of incomplete and ambiguity averse preferences, mimeo
- [22] Maccheroni, F., M. Marinacci and A. Rustichini.(2006): Ambiguity aversion, robustness and the variational representation of preferences. Econometrica, 74, 1447-1498.
- [23] Mandler, M. (2005): Incomplete preferences and rational intransitivity of choice. Games and Economic Behavior, 50, 255–277.
- [24] Markowitz, H.M.(1952): Portfolio selection. Journal of Finance, 7, 77-91.
- [25] Savage, L. J.(1954): The Foundations of Statistics. Wiley, New York.
- [26] Schatten, R. (1950): A theory of cross-space. Annals of Mathematical Studies, 26, Princeton University Press.
- [27] Schmeidler, D.(1989): Subjective probability and expected utility theory without additivity, Econometrica, 57, 571-587.
- [28] Strzalecki, T. (2007): Axiomatic Foundations of Multiplier Preferences, mimeo.
- [29] Tobin, J. (1958): Liquidity preference as behavior toward risk. Review of Economic Studies, 25, 65-86.
- [30] von Neumann, J. and O. Morgenstern.(1944): Theory of Games and Economic Behavior. Princeton University Press, Princeton.